Guidelines for Strain-Based Design and Assessment (SBDA) of Pipeline Segments

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1 Introduction

1.1 Background

Strain-based design and assessment (SBDA) criteria refer to the design/assessment principles and procedures for pipelines experiencing high longitudinal strain under primarily displacement controlled loading conditions.

For static loadings, at least three limit states (i.e., failure modes) should be considered for the SBDA: tensile rupture, compressive buckling, and burst. For all the three limit states, the SBDA consists of two key components: load and resistance. The pipeline integrity can be determined by comparing the load with the resistance.

The load corresponding to tensile rupture, compressive buckling, and burst, is tensile strain demand, compressive strain demand, and operating pressure, respectively. The resistance to the tensile rupture, compressive buckling, and burst, is tensile strain capacity, compressive strain capacity, and burst pressure, respectively.

1.2 Contents of this Document

Guidelines for determining the resistance of a pipeline to high longitudinal strain (in general, ≥ 0.5%), i.e., tensile strain capacity, compressive strain capacity, and burst pressure, are given in this document. The guidelines were developed from a multi-year research project supported by PHMSA. The details about the technical work supporting the presented guidelines can be found in the project report [1].

The guidelines cover three common features existing in a pipeline, i.e., metal-loss type of corrosion anomalies, plain dents, and girth welds. Both regular girth welds joining pipes of equal wall thicknesses and transition girth welds joining pipes of unequal wall thicknesses are covered.

Not all the three limit states (failure modes) pose meaningful threats to a certain feature. For each feature, the guidelines are given only for the failure modes which pose meaningful threats, i.e.,

- corrosion anomalies (Section 2): tensile rupture, compressive buckling, and burst;
- plain dents (Section 4): compressive buckling; and
- girth welds (Section 5): tensile rupture and compressive buckling.

The guidelines for corrosion anomalies and plain dents are targeted for in-service assessment. The guidelines for girth welds can be applied to both design of new pipelines and assessment of in-service pipelines.

1.3 Limitations

The guidelines include two levels of assessment procedures. The Level I procedures contain assessment diagrams and/or equations. The Level II procedures contain detailed procedures for conducting case-specific finite element analyses.

The Level I procedures were developed from parametric finite element analyses and large-scale tests conducted in the PHMSA project [1]. However, due to the time and budget limit, the scope of the PHMSA project covers limited ranges for the input parameters. As a result, some Level I assessment diagrams or equations have limited applicable ranges of input parameters or high-degree built-in conservative assumptions. Future work is required to further refine those assessment diagrams and equations and extend their applicable ranges.

In addition, the guidelines cover the limit states under static loading only. Fatigue failure is a limit state under cyclic loading for SBDA. The cyclic loading can be caused by pressure and temperature variation and as well as ground movement. The cyclic loading is not in the scope of the PHMSA project [1]. Therefore, the guidelines do not cover the fatigue limit state. Future work is needed to extend the guidelines for fatigue assessment.

2 Material Specifications for Strain-Based Design

2.1 General Material Specification for Strain-Based Design

Existing material specifications for typical pipeline projects focus on pipe circumferential properties for pressure containment. Those material specifications are not adequate for strain-based design projects due to the high design strain in the pipe longitudinal direction. For strain-based design projects, pipe longitudinal properties need to be specified. The additional material specifications for strain-based design projects are given below[1]:

- Upper and lower bound pipe longitudinal properties including yield strength, tensile strength, uniform strain, and pipe Y/T ratio;

  Note: it is recommended to request pipe longitudinal properties including yield strength, ultimate tensile strength, uniform strain, and Y/T ratio in mill certificates (MTRs);

- Upper and lower bound full pipe stress-strain curves in longitudinal and circumferential directions; and

  Note: it is recommended to request full pipe stress-strain curves in both longitudinal and circumferential directions in mill certificates (MTRs);

- The effects of pipe coating (such as preparation and application temperatures and times) on pipe properties should be considered.

2.2 Additional Specifications for Transition Girth Welds

The tensile strain capacity (TSC) of a transition girth weld was found to be greatly affected by the strength difference between the thick and thin pipes of the girth weld. The existing pipe strength and thickness specifications for the transition weld focusing on pressure containment (e.g., ASME B31.8) are not adequate for the pipes subjected to high longitudinal strain (i.e., for SBD).

Enhanced pipe strength and wall thickness specifications for transition welds are provided to address both pressure containment and longitudinal strain. The enhanced specifications prevent strain localization in the pipe wall thickness transition area and enable reasonable TSC in the pipe.

The enhanced pipe strength and thickness specifications for the counterbore-tapered welds are given below:

- The longitudinal yield and ultimate tensile strengths of the thick-wall pipe should not be less than those of the thin-wall pipe.
- The (circumferential) specified minimum yield strength (SMYS) of the thick-wall pipe should not be less than the SMYS of the thin-wall pipe.

[1] The material specifications given here are preliminary specifications, which focus the basic principles need to be followed for a strain-based design project. The specifications may not be readily applicable for an actual project. Future work is needed to refine the material specifications.

- If the wall thickness ratio is greater than 1.50, the wall thickness ratio should be treated as a maximum of 1.50 for design and assessment.

The enhanced pipe strength and thickness specifications for the back-beveled welds are given below:

- The longitudinal ultimate tensile strength of the thick-wall pipe should not be less than the longitudinal flow strength of the thin-wall pipe, where the flow strength of the thin-wall pipe is the average of the yield strength and ultimate tensile strength of the thin-wall pipe.
- $R_t \geq \max(R_G, R_y, R_u)$, where R_t is the ratio between the thickness of thick-wall pipe and that of the thin-wall pipe; R_G is the ratio between the (circumferential) SMYS of thin-wall pipe and that of the thick-wall pipe; R_y is the ratio between the longitudinal yield strength of thin-wall pipe and that of the thick-wall pipe; R_u is the ratio between the longitudinal ultimate tensile strength of the thin-wall pipe and that of the thick-wall pipe.
- If the wall thickness ratio (R_t) is greater than 1.50, the wall thickness ratio should be treated as 1.50 for design and assessment.

3 Assessment of Corrosion Anomalies under High Longitudinal Strain

3.1 Scope

This section provides guidelines for assessing the resistance of corroded pipe segments to three failure modes when subjected to longitudinal strain: burst, tensile rupture, and compressive buckling. The output of the guidelines includes burst pressure, tensile strain capacity, and compressive strain capacity. The output of the guidelines can be used for the assessment of in-service pipelines.

The applicable conditions and exclusions of the guidelines are given in Sections 3.2 and 3.3, respectively. The required parameters are given in Section 3.4. The assessment procedures for the burst pressure, tensile strain capacity, and compressive strain capacity are given in Sections 3.5, 3.6, and 3.7, respectively.

3.2 Acceptable Applications

The guidelines are applicable to:

- Metal loss type of corrosion anomalies on pipe inside or outside surface, including general corrosion, longitudinal and circumferential grooves that are not too sharp (see Exclusions in the next section), and pitting; and
- Pipe segments subjected to displacement-controlled longitudinal loading, e.g., stable slope movement.

3.3 Exclusions

The guidelines cannot be applied in the following circumstances:

- Crack-like planar anomalies such as stress corrosion cracks;
- Slotting/groove corrosion with the short dimension in the pipe longitudinal or circumferential direction smaller than one pipe wall thickness;
- Corrosion anomalies interacting with other anomalies (e.g., gouge, dent, etc.) or girth/seam welds;
- Interacting corrosion anomalies;
- Pipe materials showing creep[2] behaviors under operating conditions; and
- Pipe segments subjected to load-controlled longitudinal loading, e.g., free span.

3.4 Required Parameters

The parameters listed below are required for the assessment of one or multiple failure modes. The required parameters include:

- Dimensions of the pipe segment, including pipe outside diameter (D) and pipe wall thickness (t) as shown in Figure 3-1;

[2] Creep is the tendency of a solid material to deform permanently as a result of long-term exposure to high stress that is still below the yield strength of the material, especially when subjected to heat for long periods.

- Dimensions of the metal loss type of corrosion, including depth (d_c), circumferential width (W_c, length of corrosion along pipe circumferential direction), and longitudinal length (L_c, length of corrosion along pipe longitudinal direction) as shown in Figure 3-1;
- Mechanical properties of the pipe material, including yield strength (σ_y) and Y/T ratio (R_{YT}) or ultimate tensile strength (σ_u);
- Operating pressure of the pipeline (p_i); and
- Longitudinal strain demand (for burst pressure only).

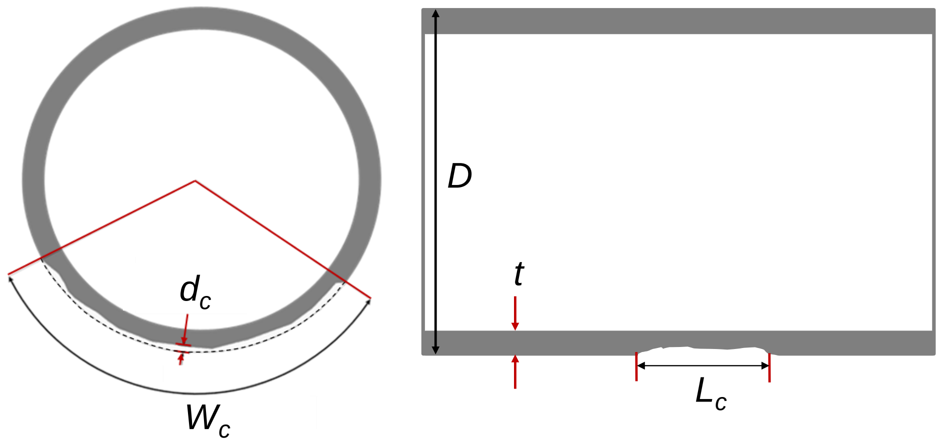

Figure 3-1 Dimensions of pipe segment and corrosion

3.5 Assessment of Burst Pressure of Pipe Segments with Corrosion

3.5.1 Overview

The procedures in this section determine the burst pressure of a pipe segment containing a metal loss type of corrosion subjected to longitudinal compressive strain resulted from bending-dominant deformation. These procedures were developed based on the studies presented in Section 5.4 of the PHMSA project report [1].

For the pipe segment subjected to longitudinal tensile strain or no longitudinal strain, the burst pressure can be determined using existing industry standards, such as ASME B31G [2], without considering the longitudinal strain (i.e., the effect of the tensile strain on the burst pressure can be neglected).

The burst pressure corresponds to an ultimate limit state. If the burst pressure (with safety factor) is exceeded, repair is required. Two different levels of assessment procedures are provided. The Level I procedures (Section 3.5.4) consist of easy-to-use equations. The Level II procedures (Section 3.5.5) are case-specific finite element analyses. The Level I procedures are based on certain conservative assumptions and have limited applicable range. If the Level I procedures are not applicable or the Level I assessment results become too restrictive, the Level II procedures can be used.

3.5.2 Definition of Burst Pressure

In the guidelines, the burst pressure is defined as the maximum pressure that the corroded pipe can withstand before any leak or rupture.

3.5.3 Determine Required Parameters

1) STEP 1 – Determine the depth (d_c) of the corrosion anomalies. The corrosion depth is the maximum depth in the metal loss area.
2) STEP 2 – Determine the magnitude of the longitudinal compressive strain demand, i.e., $\left|\varepsilon_c^{dem}\right|$. The strain demand should be the average compressive strain within a 2D gauge length (l_0) centered at the location of the corrosion (D is the pipe outside diameter), as shown in Figure 3-2. The strain demand should be obtained during operations. It can be obtained through IMU strain measurements or from strain demand numerical simulations (e.g., pipe-soil interaction simulations). It should be noted that IMU tools measure only bending strain. The membrane compressive strain due to other effects such as the temperature effect should be estimated and added to the measured bending strain. For the strain demand numerical simulations, the corrosion anomaly should be built in the simulation models. A proper safety factor (γ_{sd}) should be applied for the strain demand. The safety factor should be determined based on the methods and/or tools used to determine the strain demand. The unit of ε_c^{dem} is mm/mm (in/in), e.g., if the longitudinal compressive strain is -2%, $\left|\varepsilon_c^{dem}\right|$ should be set at 0.02.

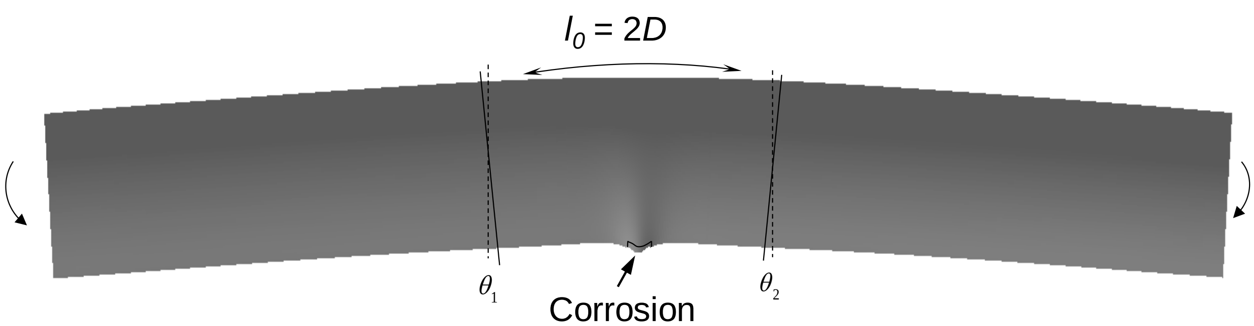

Figure 3-2 Schematic drawing of compressive strain demand measurement

3) STEP 3 – Confirm the applicable range for Level I assessment procedures. Proceed to Section 3.5.4 if all the following conditions are satisfied. Proceed to Section 3.5.5 if any of the following conditions is not satisfied.

$$L_c/\sqrt{Dt} \le 1.3 \,,$$

$$L_c/t > 1.0 \,,$$

$$W_c/\sqrt{Dt} \le 1.3 \,,$$

$$W_c/t > 1.0 \,,$$

$\left|\varepsilon_c^{dem}\right| \cdot \gamma_{sd} \le 0.020$, and

$d_c / t \le 0.40$.

Note: The maximum applicable compressive strain is 2%. For most pipes, wrinkles will be formed at the corrosion location under 2% compressive strain. Therefore, there exists interaction between the corrosion and wrinkle. The assessment procedures given in this section (Section 3.5) are applicable for corrosion-wrinkle interaction.

3.5.4 Assessment Procedures (Level I)

1) STEP 1 – Determine the burst pressure (P_b) of the pipe segment containing the corrosion anomaly for no longitudinal load from existing standards, e.g., ASME B31G [2].
   Note: The level of accuracy and conservatism of the calculated burst pressure depends on the selected standards [3].
2) STEP 2 – Determine the burst pressure ($P_b^{\varepsilon_c}$) of the pipe segment subjected to the longitudinal compressive strain using the following equation:

$$P_b^{\varepsilon_c} = \gamma_b P_b \cdot \left(1.00 - 5.76\left|\varepsilon_c^{dem}\right| \cdot \gamma_{sd}\right), \tag{3-1}$$

   where, γ_b is the safety factor applied to the burst pressure. If no safety factor is used in calculating P_b in Step 1, it is recommended that $\gamma_b \le 0.80$. Otherwise, $\gamma_b = 1.0$. The unit of $P_b^{\varepsilon_c}$ is the same with the unit of P_b determined in Step 1.

3.5.5 Assessment Procedures (Level II)

3.5.5.1 <u>General Requirement on the Finite Element Models</u>

For the Level II assessment, case-specific finite element analyses (FEA) are required. Three-dimension solid (brick) elements are recommended in order to capture the shape of the corrosion anomalies and the stress/strain concentration in the corrosion area. Adequate mesh refinement (i.e., proper element size) should be determined through mesh convergence studies. The length of the pipe model should be kept long enough to avoid the boundary conditions applied at the pipe ends affecting the corrosion behavior (i.e., end effects).

3.5.5.2 <u>Determination of Input Parameters</u>

The input parameters of the FEA models (e.g., pipe geometries, material properties, etc.) can be determined using the following recommendations:

1) The nominal pipe outside diameter and wall thickness should be used.
2) Modeling the corrosion with its actual shape is preferred. If the modeling of the actual shape is not feasible, the corrosion can be modeled as a rectangle shape with flat bottom (i.e., uniform depth). The size of the corrosion, i.e., depth (d_c), circumferential width (W_c), and longitudinal length (L_c) can be determined following the procedures given in Section 5.3.3 of API 579 [4]. However, if there are longitudinal grooves inside a general

corrosion, the smallest W_c of all the longitudinal grooves should be used as the circumferential width (W_c) of the anomaly.

3) The circumferential tensile stress-strain curve of the actual pipe joint showing the lower-bound ultimate tensile strength should be used. If the actual stress-strain curve is not available, the full stress-strain curve can be constructed following the procedures given in Section 6.1 of the PHMSA project report [5] using the pipe yield and ultimate tensile strengths. The lower-bound ultimate tensile strength in the circumferential direction and the corresponding yield strength of the actual pipe joint should be used. If the actual pipe strength is not available, the lower-bound pipe tensile strength and the corresponding yield strength should be estimated by considering the pipe grade, vintage, chemical composition, type (e.g., UOE, ERW, etc.), strength range (e.g., in project specifications, relevant pipe standards (e.g., API 5L), or mill certificates), properties of similar pipes on the same pipeline, and/or conditions for pipe coatings.

3.5.5.3 <u>Loading and Results</u>

The recommended loading steps for the FEA are given in the following:

1) STEP 1 - Keep longitudinal load free and apply internal pressure to reach the maximum allowable operating pressure (MAOP);
2) STEP 2 - Keep the internal pressure at MAOP and apply rotation at both ends of the pipe to reach the target longitudinal compressive strain (the longitudinal compressive strain should be measured as the average compressive strain within a 2D gauge length centered at the corrosion location, see Figure 3-2); and
3) STEP 3 - Fix the rotation angle at both pipe ends and increase the internal pressure until the maximum pressure is reached. For this step, the RIKS method [6] is recommended.

The burst pressure is the maximum internal pressure.

3.6 Assessment of Tensile Strain Capacity of Pipe Segments with Corrosion

3.6.1 Overview

The procedures given in this section determine the tensile strain capacity (i.e., resistance to tensile rupture) of a pipe segment containing metal loss type of corrosion anomalies subjected to bending deformation and/or axial tension. These procedures were developed based on the studies presented in Section 5.2 of the PHMSA project report [1].

The tensile strain capacity corresponds to an ultimate limit state. If the tensile strain capacity (with safety factor) is exceeded, repair is required. Two different levels of assessment procedures are provided. The Level I procedures (Section 3.6.4) consist of easy-to-use graphics and equations. The Level II procedures (Section 3.6.5) are case-specific finite element analyses. The Level I procedures are based on certain conservative assumptions and have limited applicable range. If the Level I procedures are not applicable or the Level I assessment results become too restrictive, the Level II procedures can be used.

3.6.2 Definition of Tensile Strain Capacity

The tensile strain capacity is the maximum tensile strain that the corroded pipe can withstand before any leak or rupture. In the guidelines, the tensile strain capacity is designated to capture the overall capacity of the pipe to accommodate global/nominal longitudinal tension and bending deformation.

In order to properly represent the nominal strain, the tensile strain capacity was obtained under longitudinal tension and was measured in such a way that the reported tensile strain capacity was not affected by the strain concentration in the corrosion area. It is known that the tensile strain capacity of a pipe under longitudinal tension is lower than that under bending. Therefore, the tensile strain capacity given in the guidelines can be used for bending deformation conservatively.

The pipe integrity is usually determined by comparing strain capacity with strain demand. To properly use the strain capacity determined by the guidelines, consistency between the measures of strain demand and strain capacity must be assured. Otherwise, the assessment results may become either overly conservative or not conservative.

The longitudinal strain demand should be obtained during operations. The strain demand can be measured by IMU tools or calculated from numerical simulations (e.g., finite element analyses of pipe-soil interactions).

For most IMU measurements, the reported strain demand is the average strain in a 10-ft gauge length, which can be affected by the strain concentration induced by a corrosion anomaly. If the area of the strain concentration induced by the corrosion anomaly is much smaller than the 10-ft gauge length (which is typically the case), the IMU strain is a good approximation of the nominal strain demand. Otherwise, the IMU strain can be greater than the nominal strain and using the IMU strain as the strain demand (i.e., compare the IMU strain with the strain capacity in the guidelines) can result in conservative results. It should be noted that the IMU tools measure only bending strain. The membrane/cable tensile strain due to other effects such as the temperature effect and the elongation of a bent pipe should be estimated and added to the IMU measured strain.

For most strain demand numerical simulations, the corrosion anomalies are not built in the numerical models. For such circumstances, the strain demand calculated by the numerical simulations does not capture the strain concentration induced by the corrosion anomaly. As a result, the calculated strain demand from the numerical simulations can be directly compared with the strain capacity in the guidelines.

3.6.3 Determine the Required Parameters

1) STEP 1 – Determine the pipe outside diameter (D) and wall thickness (t). The nominal pipe outside diameter (D) and nominal wall thickness (t) of the pipe joint containing the metal loss corrosion should be used.

2) STEP 2 – Determine the operating pressure (p_i). The maximum pressure during normal operation should be used. If the actual operating pressure is not available, the maximum allowable operating pressure (MAOP) should be used.
3) STEP 3 – Determine the pipe yield-to-tensile strength ratio (R_{YT}), i.e., Y/T ratio. The upper-bound Y/T ratio in the longitudinal direction of the actual (if available) pipe joint should be used. If the actual pipe Y/T ratio is not available, the upper-bound Y/T ratio should be estimated by considering the pipe grade, vintage, chemical composition, type (e.g., UOE, ERW, etc.), strength range (e.g., in project specifications, relevant pipe standards (e.g., API 5L), or mill certificates), properties of similar pipes on the same pipeline, and/or pipe coating conditions. For modern micro-alloyed linepipe steels, if proper pipe coating procedures are followed to avoid the change of pipe properties (e.g., fusion bonded epoxy coating ≤ 200°C (392°F) and ≤ 5 minutes[3]), the following equation can be used as a starting point[4]:

$$R_{YT} = \max\left(0.84, \frac{1}{1+2\left(21.75/\sigma_{SMYS}\right)^{2.30}}\right) \tag{3-2}$$

where σ_{SMYS} is the SMYS of the pipe and the unit of σ_{SMYS} is ksi.

Note: If the pipe Y/T ratio in the circumferential direction is significantly higher than that in the longitudinal direction, using the Y/T ratio of the longitudinal direction can overestimate the strain capacity. For such circumstances, it is recommended to use the average of the Y/T ratios in the longitudinal and circumferential directions to calculate the strain capacity.

4) STEP 4 – Determine the pipe yield strength (σ_y). The lower-bound pipe yield strength in the longitudinal and circumferential directions of the actual pipe joint should be used. If the actual pipe strength is not available, the lower-bound pipe yield strength should be estimated by considering the pipe grade, vintage, chemical composition, type (e.g., UOE, ERW, etc.), strength range (e.g., in project specifications, relevant pipe standards (e.g., API 5L), or mill certificates), properties of similar pipes on the same pipeline, and/or conditions for pipe coatings.
5) STEP 5 – Determine the depth (d_c), circumferential width (W_c), and longitudinal length (L_c) of the corrosion anomalies.

Option I: The depth (d_c) is the maximum depth in the metal loss area. The width (W_c) and length (L_c) should be determined using the procedures in Section 5.3.3 of

[3] The example coating temperature and time were obtained from published data for specific pipes. The users should verify the proper coating temperature and time for their pipes.

[4] The equation was derived from Eq. (A-3) in API 1104 Appendix A (2007 Errata) by assuming that the flow stress equals the average of the yield and ultimate tensile strengths.

API 579 [4]. However, if there are circumferential grooves inside a general corrosion, the smallest L_c of all the circumferential grooves should be used as the longitudinal length (L_c) of the anomaly.

Option II: Determine the above parameters using river bottom profiles and equivalent area methods (not applicable for general corrosion containing circumferential grooves inside).

- The river bottom profile is the path traversing the deepest locations of a metal loss area along either pipe longitudinal or circumferential directions (Figure 3-3). The paths along the pipe longitudinal and circumferential directions are referred to as the longitudinal and circumferential river bottom profiles, respectively.
- The area of the longitudinal (A_c^l) or circumferential/hoop (A_c^h) river bottom profile is the projected area of the corresponding profile on the pipe circumferential or longitudinal cross sections, respectively (Figure 3-3).
- The depth (d_c) of the corrosion anomaly is the maximum depth of the metal loss area (Figure 3-4). The longitudinal length (L_c) is the area of the longitudinal river bottom profile (A_c^l) divided by d_c. The circumferential width (W_c) is the area of the circumferential river bottom profile (A_c^h) divided by d_c.

6) STEP 6 – Calculate normalized corrosion dimensions: depth (d_c/t), circumferential width ($W_c/\sqrt{Dt}$), and longitudinal length ($L_c/\sqrt{Dt}$)

7) STEP 7 – Calculate pressure factor (f_p): $f_p = \dfrac{p_i D}{2t\sigma_y}$

8) STEP 8 – Confirm the applicable range for Level I assessment procedures. Proceed to Section 3.6.4 if all the following conditions are satisfied. Proceed to Section 3.6.5 if any of the following conditions is not satisfied.

$L_c/\sqrt{Dt} \le 3.4$,

$L_c/t > 1.0$,

$W_c/\sqrt{Dt} \le 3.4$,

$W_c/t > 1.0$,

$d_c/t \le 0.25$,

$R_{YT} \le 0.92$, and

$f_p \le 0.80$.

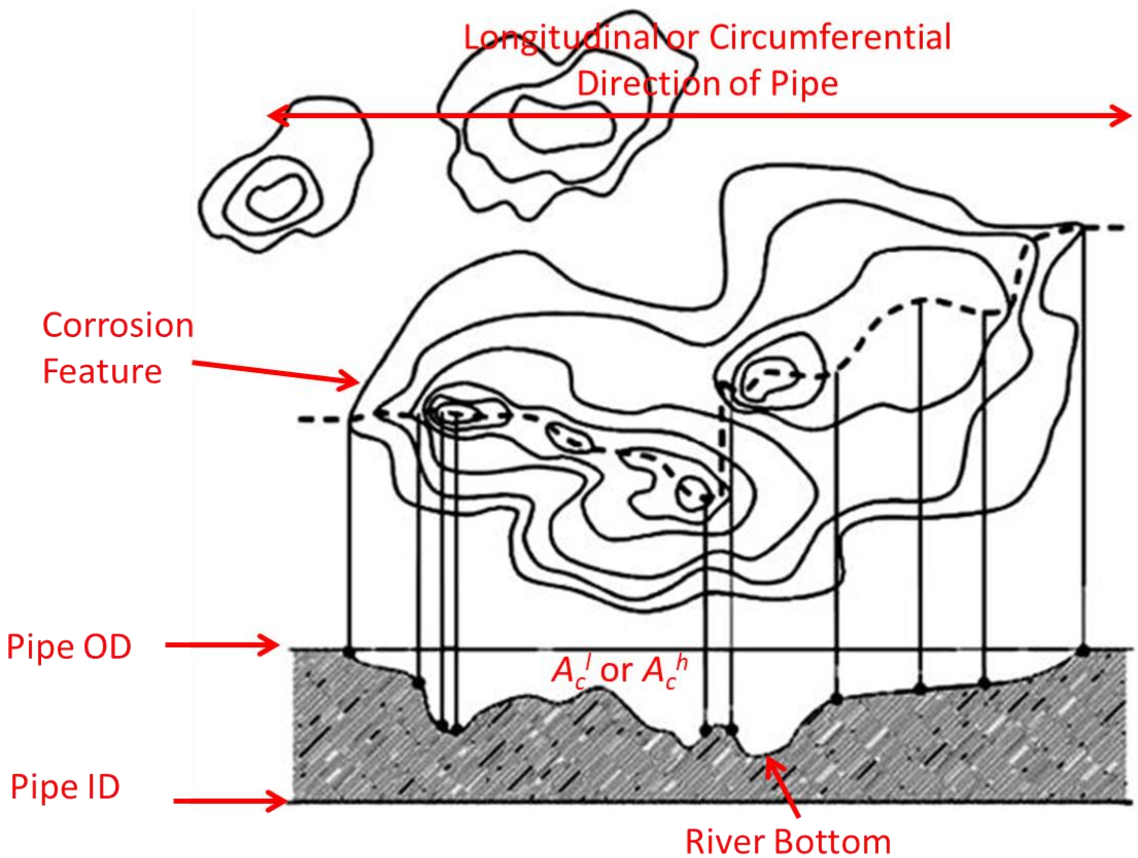

Figure 3-3 Longitudinal or circumferential river bottom profile of corrosion[5]

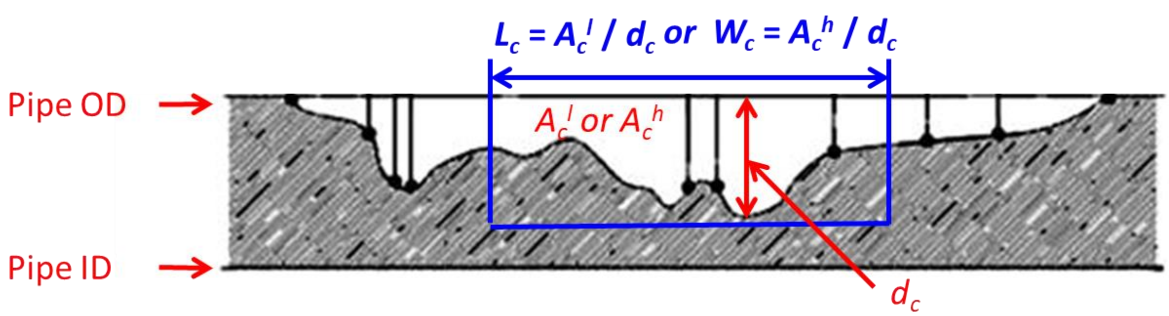

Figure 3-4 Demonstration of the effective area method[6]

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[5] The schematic drawings were modified from those originally presented by Karami, M, 2012, "Review of Corrosion Role in Gas Pipeline and Some Methods for Preventing It," J. Pressure Vessel Technol., 134 (5).

[6] See Footnote 5.

3.6.4 Assessment Procedures (Level I)

1) STEP 1 – Calculate reference tensile strain capacity ($\varepsilon_{t,corr}^{ref}$) of a pipe with corrosion using Figure 3-5. Linear interpolation can be used for an intermediate width (W_c) between the given curves. For $W_c/\sqrt{Dt} < 0.34$, the curve of $W_c/\sqrt{Dt} = 0.34$ can be used.

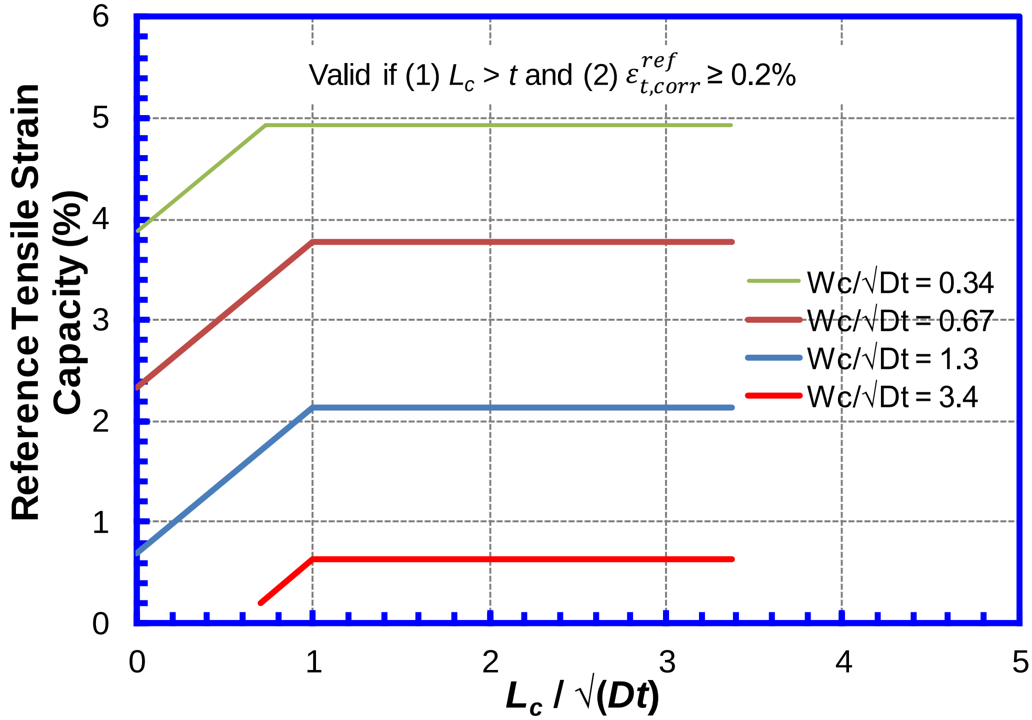

Figure 3-5 Reference tensile strain capacity[7]

2) STEP 2 – Determine the tensile strain capacity using the following equation:

$$\varepsilon_{t,corr}^{crit} = \begin{cases} \gamma_t \varepsilon_{t,corr}^{ref}, & R_{YT} \leq 0.83 \\ \gamma_t \varepsilon_{t,corr}^{ref} \left(-7.14 R_{YT} + 6.92\right), & R_{YT} > 0.83 \end{cases}, \quad (3\text{-}3)$$

where, γ_t is the safety factor applied to the tensile strain capacity. The recommended safety factor is $\gamma_t \leq 0.60$.

3.6.5 Assessment Procedures (Level II)

3.6.5.1 General Requirement on the Models

For the Level II assessment, case-specific finite element analyses (FEA) are required. Three-dimension solid (brick) elements are recommended in order to capture the shape of the corrosion anomalies and the stress/strain concentration in the corrosion area. Adequate mesh refinement

[7] Please note that when $L_c = 0$, the corrosion anomaly reduces to a crack instead of a defect-free pipe.

(i.e., proper element size) should be determined through mesh convergence studies. The length of the pipe model should be kept long enough in order to obtain a uniform strain zone (Figure 3-6), i.e., the strain in the uniform strain zone should not be affected by the strain concentration in the corrosion area and the boundary conditions applied at the pipe ends.

3.6.5.2 Determination of Input Parameters

The input parameters of the FEA models (e.g., pipe geometries, material properties, etc.) can be determined using the following recommendations:

1) The nominal pipe outside diameter and wall thickness should be used.
2) Modeling the corrosion with its actual shape is preferred. If the modeling of the actual shape is not feasible, the corrosion can be modeled as a rectangle shape with flat bottom (i.e., uniform depth). The size of the corrosion, i.e., depth (d_c), circumferential width (W_c), and longitudinal length (L_c) can be determined following the procedures given in STEP 5 of Section 3.6.3.
3) The longitudinal tensile stress-strain curve of the actual pipe joint showing lower-bound strain hardening capacity (i.e., upper-bound pipe Y/T ratio) should be used. If the actual stress-strain curve is not available, the stress-strain curve can be constructed following the procedures given in Section 6.1 of the PHMSA project report [5] using the pipe Y/T ratio and yield strength. The pipe Y/T ratio and yield strength can be determined following STEPs 3 and 4 in Section 3.6.3, respectively.

3.6.5.3 Loading and Results

The recommended loading steps for the FEA are given in the following:

1) STEP 1 - Keep longitudinal load free and apply internal pressure to reach the maximum allowable operating pressure (MAOP); and
2) STEP 2 - Keep the internal pressure at MAOP, fix the displacement of one pipe end and apply uni-axial tensile displacement to the other end until the maximum longitudinal load (i.e., the reaction force at the node where the displacement is applied) is reached.

The tensile strain capacity is the longitudinal tensile strain corresponding to the maximum longitudinal load. The longitudinal tensile strain should be measured as the average strain within a finite gauge length ($l_0 \geq D$) in the area away from the corrosion and pipe ends as shown in Figure 3-6. The average of the strains measured at the 6 and 12 o'clock positions or the average of the strains measured at the 3 and 9 o'clock positions of the pipe should be used (assuming the corrosion is centered at the 12 o'clock position).

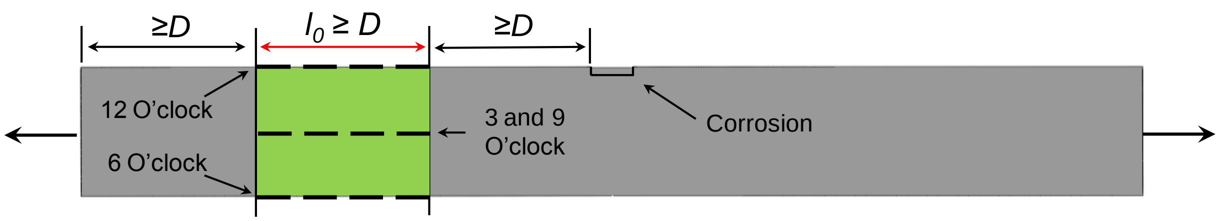

Figure 3-6 Calculation of tensile strain capacity

3.7 Assessment of Compressive Strain Capacity of Pipes with Corrosion

3.7.1 Overview

The procedures in this section determine the compressive strain capacity (i.e., resistance to compressive bucking) of a pipe segment containing metal loss type of corrosion anomalies subjected to bending-dominant deformation. The procedures are not applicable for pipes subjected to pure axial compression. These procedures were developed based on the studies presented in Section 5.3 of the PHMSA project report [1].

The compressive strain capacity defined in the guidelines corresponds to a service limit state. If the compressive strain capacity (with safety factor) is exceeded, post-wrinkle assessment [7] can be conducted to determine if repair is needed. Two different levels of assessment procedures are provided. The Level I procedures (Section 3.7.4) consist of easy-to-use graphics and equations. The Level II procedures (Section 3.7.5) are case-specific finite element analyses. The Level I procedures are based on certain conservative assumptions and have limited applicable range. If the Level I procedures are not applicable or the Level I assessment results become too restrictive, the Level II procedures can be used.

3.7.2 Definition of Compressive Strain Capacity

In the guidelines, the compressive strain capacity is defined as the compressive strain corresponding to the maximum bending moment the corroded pipe can withstand and is designated to capture the overall capacity of the pipe to accommodate global/nominal longitudinal bending deformation.

In order to properly represent the nominal strain, the compressive strain capacity was obtained under bending and was measured in such a way that the reported compressive strain capacity was not affected by the strain concentration in the corrosion area. It is known that the compressive strain capacity of a pipe under longitudinal compression is lower than that under bending. Therefore, the compressive strain capacity given in the guidelines is applicable only for bending-dominant deformation.

The pipe integrity is usually determined by comparing strain capacity with strain demand. To properly use the strain capacity determined by the guidelines, consistency between the measures of strain demand and strain capacity must be assured. Otherwise, the assessment results may become either overly conservative or not conservative.

The longitudinal strain demand should be obtained during operations. The strain demand can be measured by IMU tools or calculated from numerical simulations (e.g., finite element analyses of pipe-soil interactions).

For most IMU measurements, the reported strain demand is the average strain in a 10-ft gauge length, which can be affected by the strain concentration induced by a corrosion anomaly. If the area of the strain concentration induced by the corrosion anomaly is much smaller than the 10-ft gauge length (which is typically the case), the IMU strain is a good approximation of the nominal strain demand. Otherwise, the IMU strain can be greater than the nominal strain and using the IMU strain as the strain demand (i.e., compare the IMU strain with the strain capacity in the guidelines) can result in conservative results. It should be noted that the IMU tools measure only bending strain. The membrane compressive strain due to other effects such as the temperature effect should be estimated and added to the measured IMU strain.

For most strain demand numerical simulations, the corrosion anomalies are not built in the numerical models. For such circumstances, the strain demand calculated by the numerical simulations does not capture the strain concentration induced by the corrosion anomaly. As a result, the calculated strain demand can be directly compared with the strain capacity in the guidelines.

3.7.3 Determine the Required Parameters

1) STEP 1 – Determine the pipe outside diameter (*D*) and wall thickness (*t*). The nominal pipe outside diameter (*D*) and nominal wall thickness (*t*) of the pipe joint containing the metal loss corrosion should be used.
2) STEP 2 – Determine the operating pressure (p_i). The lower-bound pressure during normal operation should be used.
3) STEP 3 – Determine the pipe yield-to-tensile strength ratio (R_{YT}), i.e., Y/T ratio. Determine the longitudinal upper bound pipe Y/T ratio following Step 3 of Section 3.6.3.
4) STEP 4 – Determine the pipe yield strength (σ_y). The upper-bound pipe yield strength in the longitudinal and circumferential directions of the actual pipe joint should be used. If the actual pipe strength is not available, the upper-bound pipe yield strength should be estimated by considering the pipe grade, vintage, chemical composition, type (e.g., UOE, ERW, etc.), strength range (e.g., in project specifications, relevant pipe standards (e.g., API 5L), or mill certificates), properties of similar pipes on the same pipeline, and/or conditions for pipe coatings.
5) STEP 5 – Determine the depth (d_c), circumferential width (W_c), and longitudinal length (L_c) of the corrosion anomalies. The depth (d_c) is the maximum depth in the metal loss area. The width (W_c) and length (L_c) should be determined using the procedures in Section 5.3.3 of API 579 [4].
6) STEP 6 – Calculate normalized corrosion dimensions: depth (d_c/t), circumferential width ($W_c/\sqrt{Dt}$), and longitudinal length ($L_c/\sqrt{Dt}$)
7) STEP 7 – Calculate pressure factor (f_p): $f_p = \dfrac{p_i D}{2t\sigma_y}$.
8) STEP 8 – Confirm the applicable range for Level I assessment procedures. Proceed to Section 3.7.4 if all the following conditions are satisfied. Proceed to Section 3.7.5 if any of the following conditions is not satisfied.

$$L_c/\sqrt{Dt} \le 2.1 ,$$

$$L_c/t > 1.0 ,$$

$W_c / \sqrt{Dt} \le 2.1$,

$W_c / t > 1.0$,

$d_c / t \le 0.25$,

$20 \le D/t \le 51$,

$0.84 \le R_{YT} \le 0.88$, and

$f_p \ge 0.72$.

3.7.4 Assessment Procedures (Level I)

1) STEP 1 – Calculate reference compressive strain capacity ($\varepsilon_{c,corr}^{ref}$) using Figure 3-7. Linear interpolation can be used for an intermediate width (W_c) between the given curves. For $W_c / \sqrt{Dt} < 0.35$, the curve of $W_c / \sqrt{Dt} = 0.35$ can be used (see below).

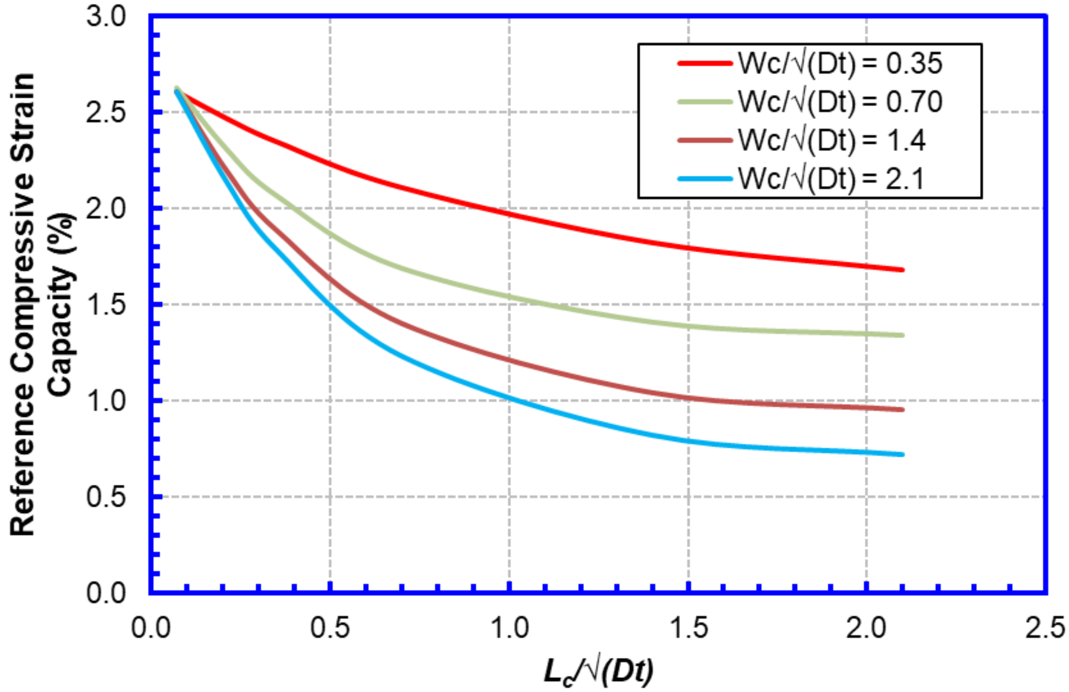

Figure 3-7 Reference compressive strain capacity[8]

2) STEP 2 – Determine the compressive strain capacity ($\varepsilon_{c,corr}^{crit}$) using the following equations:

[8] Please note that when $L_c = 0$, the corrosion anomaly reduces to a crack instead of a defect-free pipe.

$$\varepsilon_{c,corr}^{crit} = \gamma_c \varepsilon_{c,corr}^{ref} F_{DP} \tag{3-4}$$

$$F_{DP} = 539.3 \cdot (2.87 - 2.13 R_{YT}) \left(\frac{D}{t} \right)^{-1.6} \tag{3-5}$$

where, γ_c is the safety factor applied to the compressive strain capacity. The recommended safety factor is $\gamma_c \le 0.80$.

3.7.5 Assessment Procedures (Level II)

3.7.5.1 General Requirement on the Models

For the Level II assessment, case-specific finite element analyses (FEA) are required. Both three-dimensional solid (brick) elements and three-dimensional shell elements can be used for the FEA model. Adequate mesh refinement (i.e., proper element size) should be determined through mesh convergence studies. The length of the pipe model should be kept long enough in order to obtain a remote strain zone (Figure 3-8), i.e., the strain in the remote strain zone should not be affected by the strain concentration in the corrosion area and the boundary conditions applied at the pipe ends.

3.7.5.2 Determination of Input Parameters

The input parameters of the FEA models (e.g., pipe geometries, material properties, etc.) can be determined using the following recommendations:

1) The nominal pipe outside diameter and wall thickness should be used.
2) Modeling the corrosion with its actual shape is preferred. If the modeling of the actual shape is not feasible, the corrosion can be modeled as a rectangle shape with flat bottom (i.e., uniform depth). The size of the corrosion, i.e., depth (d_c), circumferential width (W_c), and longitudinal length (L_c) can be determined following the procedures given in STEP 5 of Section 3.7.3.
3) The longitudinal tensile stress-strain curve of the actual pipe joint showing lower-bound strain hardening capacity (i.e., upper-bound pipe Y/T ratio) should be used. If the actual stress-strain curve is not available, the stress-strain curve can be constructed following the procedures given in Section 6.1 of the PHMSA project report [5] using the pipe Y/T ratio and yield strength. The pipe Y/T ratio and yield strength can be determined following STEPs 3 and 4 in Section 3.7.3, respectively.

3.7.5.3 Loading and Results

The recommended loading steps for the FEA are given in the following:

1) STEP 1 - Keep longitudinal load free and apply internal pressure to reach the minimum operating pressure during normal operation;
2) STEP 2 - Keep the internal pressure at the minimum pressure in normal operation and apply rotation at both ends of the pipe until the maximum bending moment is reached (the bending moment should be measured at the wrinkle location).

The compressive strain capacity is the longitudinal compressive strain corresponding to the maximum bending moment. The longitudinal compressive strain capacity should be calculated using the strain distribution along the bottom (compressive side) of the pipe as shown in Figure 3-8. The compressive strain capacity is determined by extrapolating the strain in the remote strain zone to the center of the wrinkle. The remote strain zone is one pipe diameter (*D*) wide and 0.4*D* away from the last strain valley from the center of the wrinkle.

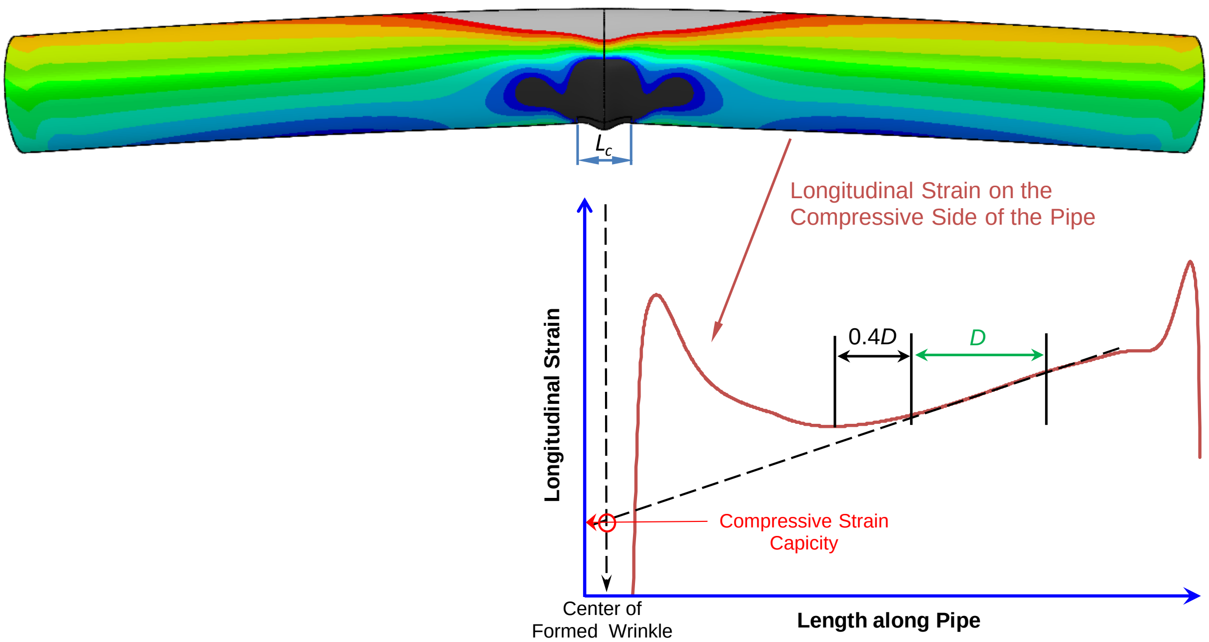

Figure 3-8 Calculation of compressive strain capacity

4 Assessment of Dents under High Longitudinal Strain

4.1 Scope

This section provides guidelines for assessing the resistance of dented pipes to compressive buckling when the pipes are subjected to longitudinal strain. The output of the guidelines is the compressive strain capacity of the dented pipe. The output of the guidelines can be used for the assessment of in-service pipelines.

The applicable conditions and exclusions of the guidelines are given in Section 4.2 and 4.3, respectively. The required parameters are given in Section 4.4. The assessment procedures for compressive strain capacity are given in Section 4.5.

As discussed in Sections 4.2 and 4.3, the guidelines are for plain dents only. It is generally believed that the plain dents have minor effects on the tensile strain capacity and burst pressure of the pipes.

4.2 Acceptable Applications

The guidelines are applicable to:

- Plain dents of smooth profiles which have no other injurious defects such as gouges or corrosion;
- Plain dents which occur on the outside surface of the pipe and are inward deviation of the pipe cross section; and
- Plain dents which are restrained or unrestrained and formed during construction or in-service.

  Note: The compressive strain capacity determined following this guideline is targeted for the unrestrained dents formed during construction. For restrained dents or dents formed in-service, the compressive strain capacity determined following this guideline tends to underestimate the actual compressive strain capacity (i.e., conservative).
- Pipe segments subjected to displacement-controlled longitudinal loading, e.g., stable slope movement.

4.3 Exclusions

The guidelines cannot be applied in the following circumstances:

- Dents interacting with girth welds, seam welds, and major structural discontinuities such as stiffening rings and piping tees;
- Pipe materials showing creep behaviors under operating conditions; and
- Pipe segments subjected to load-controlled longitudinal loading, e.g., free span.

4.4 Required Parameters

The required parameters include:

- Dimensions of the pipe segment, including pipe outside diameter (D) and pipe wall thickness (t);

- Depth of the dent under internal pressure (d_{dp}), which is measured as the maximum reduction in the diameter of the pipe in deformed configuration compared to the diameter in original configuration as shown in Figure 4-1;

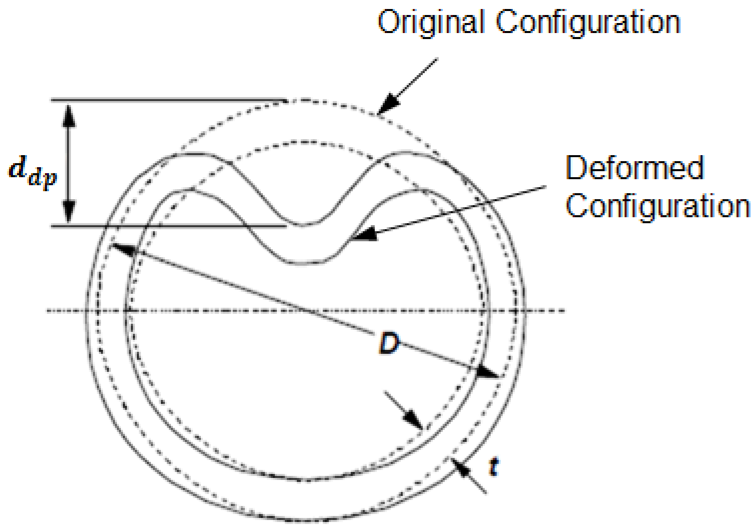

Figure 4-1 Dimensions of the pipe segment and dent

- Mechanical properties of the pipe material, including yield strength (σ_y) and Y/T ratio (R_{YT}) or ultimate tensile strength (σ_u); and
- Operating pressure of the pipeline (p_i).

4.5 Assessment of Compressive Strain Capacity of Pipes with Dents

4.5.1 Overview

The procedures in this section determine the compressive strain capacity (i.e., resistance to compressive buckling) of a pipe segment containing a plain dent subjected to bending-dominant deformation. The procedures are not applicable for pipes subjected to pure axial compression. These procedures were developed based on the studies presented in Section 6 of the PHMSA project report [1].

The compressive strain capacity defined in the guidelines corresponds to a service limit state. If the compressive strain capacity (with safety factor) is exceeded, post-wrinkle assessment [8] can be conducted to determine if repair is needed. Two different levels of assessment procedures are provided. The Level I procedures (Section 4.5.4) consist of easy-to-use equations. The Level II procedures (Section 4.5.5) are case-specific finite element analyses. The Level I procedures are based on certain conservative assumptions and have limited applicable range. If the Level I procedures are not applicable or the Level I assessment results become too restrictive, the Level II procedures can be used.

The assessment equations given in the Level I procedures are in the form of add-on equations to the compressive strain models developed in a prior PHMSA sponsored project [9]. The dent is treated as an equivalent geometry imperfection.

4.5.2 Definition of Compressive Strain Capacity

In the guidelines, the compressive strain capacity (CSC) is defined as the compressive strain corresponding to the maximum bending moment that the dented pipe can withstand. Since small wrinkles can be formed in the pipe when the bending moment reaches the maximum value, strain localization can be found near the wrinkle.

Two methods are used in the guidelines to measure the compressive strain capacity (CSC), i.e., 2D CSC ($\varepsilon_{c,dent}^{crit,2D}$) and CSC by extrapolation ($\varepsilon_{c,dent}^{crit,ex}$). The 2D CSC ($\varepsilon_{c,dent}^{crit,2D}$) follows the traditional definition of the CSC used for plain pipes, i.e., the average compressive strain within a 2*D* (*D* is the pipe outside diameter) gauge length centered at the wrinkle location. The 2D CSC can be affected by the strain localization at the wrinkle.

The CSC by extrapolation ($\varepsilon_{c,dent}^{crit,ex}$) is the strain determined in such a way that the CSC is not affected by the strain localization at the wrinkle. The CSC by extrapolation is designated to capture the overall capacity of the dented pipe to accommodate global/nominal longitudinal bending deformation.

Both the 2D CSC ($\varepsilon_{c,dent}^{crit,2D}$) and CSC by extrapolation ($\varepsilon_{c,dent}^{crit,ex}$) were obtained under bending. It is known that the CSC of a pipe under longitudinal compression is lower than that under bending. Therefore, the CSC given in the guidelines is applicable only for bending-dominant deformation.

The pipe integrity is usually determined by comparing strain capacity with strain demand. To properly use the strain capacity determined by the guidelines, consistency between the measures of strain demand and strain capacity must be assured. Otherwise, the assessment results may become either overly conservative or not conservative.

The longitudinal strain demand should be obtained during operations. The strain demand can be measured by IMU tools or calculated from numerical simulations (e.g., finite element analyses of pipe-soil interactions).

For most IMU measurements, the reported strain demand is the average strain in a 10-ft gauge length. The 10-ft gauge length is typically much greater than 2*D* and much greater than the area of strain concentration induced by the wrinkle. For such circumstances, the strain demand is close to the nominal strain and therefore, the CSC by extrapolation ($\varepsilon_{c,dent}^{crit,ex}$) should be used. If the reported strain demand is measured with a gauge length equal to or less than 2D, the 2D CSC ($\varepsilon_{c,dent}^{crit,2D}$) can be used. It should be noted that the IMU tools measure only bending strain. The membrane compressive strain due to other effects such as the temperature effect should be estimated and added to the measured IMU strain.

For most of strain demand numerical simulations, beam-type elements are used and wrinkle formation is not allowed. Therefore, the strain demand calculated by such numerical simulations does not capture the strain concentration induced by wrinkles. For such circumstances, the CSC by extrapolation ($\varepsilon_{c,dent}^{crit,ex}$) should be used.

4.5.3 Determine the Required Parameters

1) STEP 1 – Determine the pipe outside diameter (D) and wall thickness (t). The nominal pipe outside diameter (D) and nominal wall thickness (t) of the pipe joint containing the dent should be used.
2) STEP 2 – Determine the operating pressure (p_i). The lower-bound pressure during normal operation should be used.
3) STEP 3 – Determine the pipe yield-to-tensile strength ratio (R_{YT}), i.e., Y/T ratio. Determine the longitudinal upper bound pipe Y/T ratio following Step 3 of Section 3.6.3.
4) STEP 4 – Determine the pipe yield strength (σ_y). Determine the upper-bound pipe yield strength following Step 4 in Section 3.7.3.
5) STEP 5 – Determine the dent depth in pressurized conditions (d_{dp}). The maximum dent depth at the internal pressure equal or lower than the lower-bound pressure during normal operation should be used. If the dent depth is measured at the internal pressure which is higher than the lower-bound pressure in normal operation, the measured depth should be corrected (usually increased) for the pressure effect.
6) STEP 6 – Calculate normalized dent depth (d_{dp}/D)
7) STEP 7 – Calculate the pressure factor (f_p): $f_p = P_i D/(2t\sigma_y)$
8) STEP 8 – Confirm the applicable range for Level I assessment procedures. Proceed to Section 4.5.4 if all the following conditions are satisfied. Proceed to Section 4.5.5 if any of the following conditions is not satisfied.

$51 \le D/t \le 72,$

$0.77 \le R_{YT} \le 0.88,$

$0.72 \le f_p \le 0.80,$ and

$0 \le d_{dp}/D \le 0.08.$

4.5.4 Assessment Procedures (Level I)

1) STEP 1 – Calculate the normalized equivalent geometry imperfection height (h_g^e/t) of the dent using the following equation,

$$h_g^e/t = 0.01 * [0.019 * (D/t) + 1.4]\left(100 * d_{dp}/D\right)^{[-0.023*(D/t)+1.9]} \tag{4-1}$$

where the d_{dp}/D, D/t, and h_g^e/t are in the unit of mm/mm (in/in).

2) STEP 2 – Calculate the 2D CSC ($\varepsilon_c^{crit,2D}$) without safety factor with the CSC equations given in Appendix B [9] by replacing the normalized geometry imperfection height (h_g/t) with the normalized equivalent geometry imperfection height (h_g^e/t) calculated in STEP 1.

3) STEP 3 – The 2D CSC with a safety factor ($\varepsilon_{c,dent}^{crit,2D}$) can be determined as

$$\varepsilon_{c,dent}^{crit,2D} = \gamma_c \varepsilon_c^{crit,2D}, \tag{4-2}$$

where, γ_c is the safety factor applied to the CSC. The recommended safety factor is $\gamma_c \leq 0.80$. The units of $\varepsilon_c^{crit,2D}$ and $\varepsilon_{c,dent}^{crit,2D}$ calculated from the above equations are %. For example, if the CSC is 2.0% (i.e., 0.02 mm/mm or in/in), the calculated $\varepsilon_c^{crit,2D}$ or $\varepsilon_{c,dent}^{crit,2D}$ is 2.0.

4) STEP 3 – Calculate the compressive strain capacity by extrapolation ($\varepsilon_{c,dent}^{crit,ex}$) with the following equation,

$$\varepsilon_{c,dent}^{crit,ex} = 1.03 * \varepsilon_{c,dent}^{crit,2D} - 0.20, \quad (4\text{-}3)$$

where, the units of $\varepsilon_{c,dent}^{crit,ex}$ and $\varepsilon_{c,dent}^{crit,2D}$ calculated from the above equations are %. For example, if the CSC is 2.0% (i.e., 0.02 mm/mm or in/in), the calculated $\varepsilon_{c,dent}^{crit,ex}$ or $\varepsilon_{c,dent}^{crit,2D}$ is 2.0.

4.5.5 Assessment Procedures (Level II)

4.5.5.1 General Requirement on the Models

For the Level II assessment, case-specific finite element analyses (FEA) are required. Both three-dimensional solid (brick) elements and three-dimensional shell elements can be used to model the pipe. Adequate mesh refinement (i.e., proper element size) should be determined through mesh convergence studies. The length of the pipe model should be kept long enough so that there exists a remote strain zone of at least 1D long between the dent and pipe ends, in which the strain is not affected by the strain concentration occurred at either the dent or the pipe ends. The indenter can be simulated as an analytical rigid surface of a sphere shape.

4.5.5.2 Determination of Input Parameters

The input parameters of the FEA models (e.g., pipe geometries, material properties, etc.) can be determined using the following recommendations:

1) The nominal pipe outside diameter and wall thickness should be used.
2) The actual indenter shape and size should be used. If the actual indenter is not known, the indenter can be modeled as a sphere with a diameter of 2.5 to 4.5 inches.

   Note: The analysis results showed that the indenter size had a small effect on the CSC.
3) The longitudinal tensile stress-strain curve of the actual pipe joint showing lower-bound strain hardening capacity (i.e., upper-bound pipe Y/T ratio) should be used. If the actual stress-strain curve is not available, the stress-strain curve can be constructed following the procedures given in Section 6.1 of the PHMSA project report [5] using the pipe Y/T ratio and yield strength. The pipe Y/T ratio and yield strength can be determined following STEPs 3 and 4 in Section 4.5.3, respectively.

4.5.5.3 Loading Steps

If the forming conditions (i.e., in construction or in-service) and restraining conditions (i.e., restrained or unrestrained) of the dent are not known, the dent should be treated as unrestrained and formed in construction. The corresponding loading steps for the FEA are given in the following. If the forming and restraining conditions are known, the loading steps for the FEA can be modified to represent the actual conditions.

1) STEP 1 – Indent the pipe under zero internal pressure with an indentation depth of twice of the measured dent depth;
2) STEP 2 – Remove the indenter and allow the pipe to re-round;
3) STEP 3 – Apply one pressure cycle to simulate the hydrostatic test with the pressure level corresponding to the hydrostatic pressure (the pressure cycle should follow: zero pressure → hydrostatic pressure → zero pressure);
4) STEP 4 – Apply a minimum of three pressure cycles to simulate pressure variation under normal operation with the pressure level corresponding to normal operating pressure (each pressure cycle should follow: zero pressure → upper bound operating pressure → zero pressure);
5) STEP 5 – Increase the pressure to the pressure level at which the dent depth is measured and measure the simulated dent depth;
6) STEP 6 – Adjust the indentation depth in STEP 1 based on the simulated dent depth and re-do the above steps (STEP 1-5), until the simulated dent depth matches the measured depth; and
7) STEP 5 – Keep the internal pressure at the lower bound pressure in normal operation and apply rotation at both ends of the pipe to bend the pipe until the maximum bending moment is reached.

4.5.5.4 Calculation of CSC

The compressive strain capacity is the longitudinal compressive strain corresponding to the maximum bending moment. The bending moment needs to be measured at the pipe cross section at the center of the wrinkle. The procedures for calculating the 2D CSC ($\varepsilon_{c,dent}^{crit,2D}$) and CSC by extrapolation ($\varepsilon_{c,dent}^{crit,ex}$) are given below.

1) 2D CSC ($\varepsilon_{c,dent}^{crit,2D}$)

The 2D CSC ($\varepsilon_{c,dent}^{crit,2D}$) is the average compressive strain measured within a $2D$ (D is the pipe outer diameter) gauge length centered at the wrinkle, as shown in Figure 4-2. The CSC should be determined when the moment at the wrinkle location reaches the maximum. The 2D CSC ($\varepsilon_{c,dent}^{crit,2D}$) should be calculated using the following equation:

$$\varepsilon_{c,dent}^{crit,2D} = \varepsilon_t - D * (\theta_2 - \theta_1)/l_0 \quad (4\text{-}4)$$

where ε_t is the tensile strain on the tensile side of the pipe, θ_1 and θ_2 are the rotation angles (in unit of rad) of the pipe cross sections at the end of the gauge length, l_0 (= $2D$) is the gauge length, and D is the pipe outer diameter.

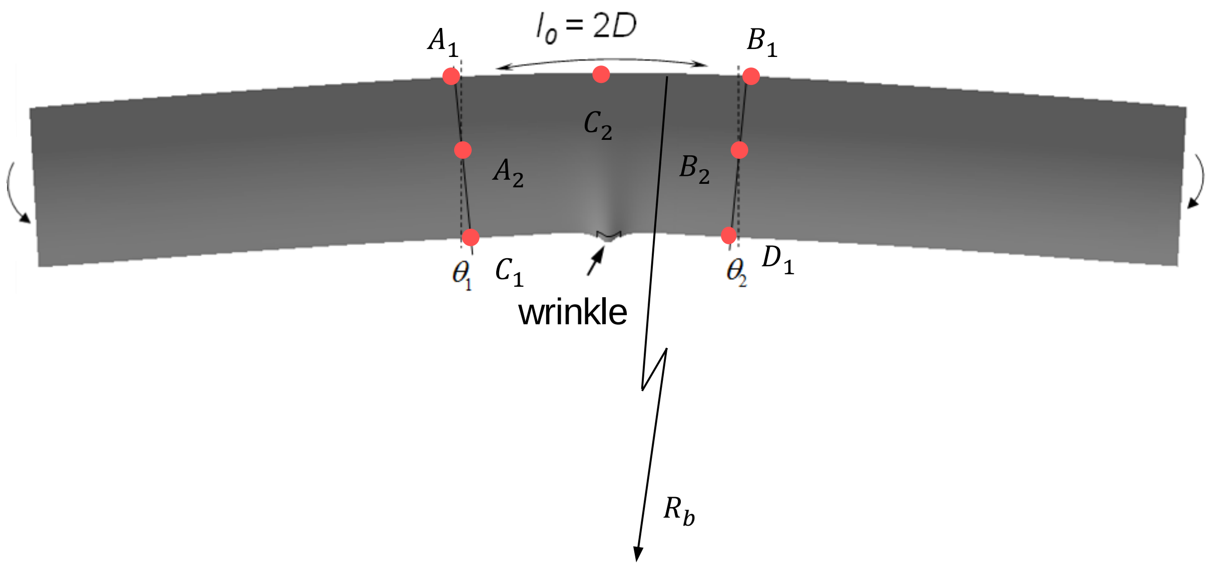

Figure 4-2 Calculation of 2D CSC for dented pipe

Depending on the method to determine the tensile strain (ε_t) and rotation angles (θ_1, θ_2), the 2D CSC ($\varepsilon_{c,dent}^{crit,2D}$) can be calculated with one of the methods given below.

- Method 1 (Option 1):

  The tensile strain (ε_t) is calculated as the average strain within the gauge length on the tensile side of the pipe by assuming the deformed pipe is a part of a circle with the radius of R_b, as shown in Figure 4-2. The radius (R_b) and rotation angles (θ_1 and θ_2) are determined using the coordinates of the four points (A_1, B_1, C_1 and D_1) as shown in Figure 4-2. The tensile strain (ε_t) is calculated by the following equation:

$$\varepsilon_t = R_b * (\theta_2 - \theta_1)/l_0 - 1 \quad (4\text{-}5)$$

- Method 1 (Option 2):

  The tensile strain (ε_t) is determined as the strain at the center of the gauge (Point C_2) on the tension side of the pipe, as shown in Figure 4-2. The rotation angles (θ_1 and θ_2) are measured at the middle height of the pipe (Points A_2 and B_2), as shown in Figure 4-2.

- Method 2:

  The 2D CSC ($\varepsilon_{c,dent}^{crit,2D}$) is directly calculated using the displacement of two points (one is $1D$ to left and the other is $1D$ to the right of the center of the wrinkle) on the bottom side of the pipe (Points C_1 and D_1), as shown in Figure 4-2.

2) CSC by Extrapolation ($\varepsilon_{c,dent}^{crit,ex}$)

The CSC by extrapolation ($\varepsilon_{c,dent}^{crit,ex}$) is determined from the strain distribution in the area sufficiently away from the wrinkle (remote strain zone) by extrapolating the strain along the outmost compressive fiber of the pipe to the wrinkle location (Figure 4-3). The remote strain zone is one pipe diameter (D) wide and $0.4D$ away from the last strain valley from the center of the wrinkle.

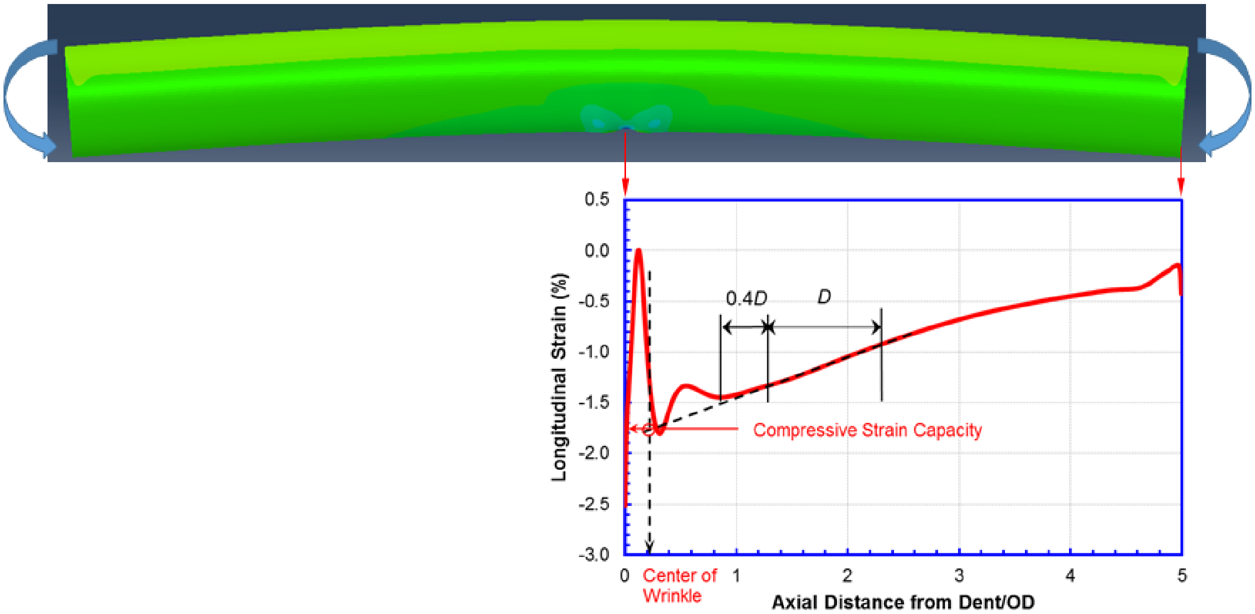

Figure 4-3 Calculation of CSC by extrapolation for dented pipe

5 Assessment of Girth Welds under High Longitudinal Strain

5.1 Scope

This section provides guidelines for assessing the resistance of pipe girth welds to two failure modes (when subjected to longitudinal strain): tensile rupture and compressive buckling. The output of the guidelines includes tensile strain capacity and compressive strain capacity. The output of the guidelines can be used for (1) design of new pipelines and (2) assessment of in-service pipelines.

The applicable conditions and exclusions of the guidelines are given in Sections 5.2 and 5.3, respectively. The required parameters are given in Section 5.4. The assessment procedures for the tensile and compressive strain capacities are given in Sections 5.5 and 5.6, respectively.

5.2 Acceptable Applications

The guidelines are applicable to:

- Girth welds containing crack-like surface-breaking planar anomalies;
  - Regular girth welds jointing pipes with equal wall thickness (Figure 5-1); and
  - Transition girth welds jointing pipes with unequal wall thickness including back-beveled joints (Figure 5-2) and counterbore-tapered joints (Figure 5-3).
- Pipe segments subjected to displacement-controlled longitudinal loading, e.g., stable slope movement.

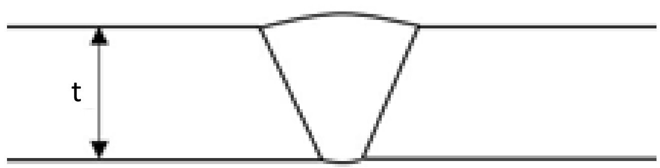

Figure 5-1 Regular girth weld

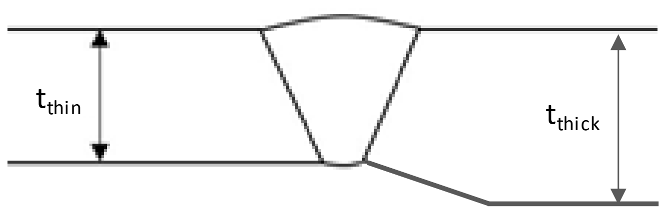

Figure 5-2 Transition girth weld (back-beveled design)

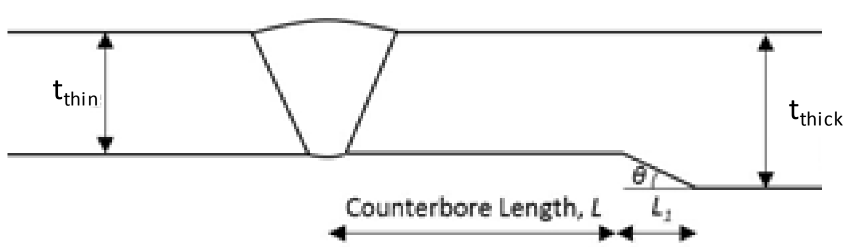

Figure 5-3 Transition girth weld (counterbore-tapered design)

5.3 Exclusions

The guidelines cannot be applied in the following circumstances:

- Girth welds interacting with other anomalies (e.g., corrosion, gouge, dent, etc.);
- Pipe materials showing creep behaviors under operating conditions; and
- Pipe segments subjected to load-controlled longitudinal loading, e.g., free span.

5.4 Required Parameters

The parameters listed below are required for the assessment of one or two failure modes. The required parameters include:

- Pipe dimensions, i.e., pipe outside diameter (D) and wall thickness (t);
- Height of pipe manufacturing geometry imperfection (h_g), as shown in Figure 5-4;
- Girth weld high-low misalignment (h) as shown in Figure 5-5;
- Size of planar anomaly, i.e., depth (a) and length ($2c$) as shown in Figure 5-6;
- Pipe mechanical properties, i.e., pipe yield strength (σ_y), Y/T ratio (R_{YT}), and ultimate tensile strengths (σ_u);
- Girth weld mechanical properties, i.e., weld ultimate tensile strength (σ_{u^w});
- Girth weld toughness properties, i.e., the apparent toughness (δ_A); and
- Operating pressure of the pipeline (p_i).

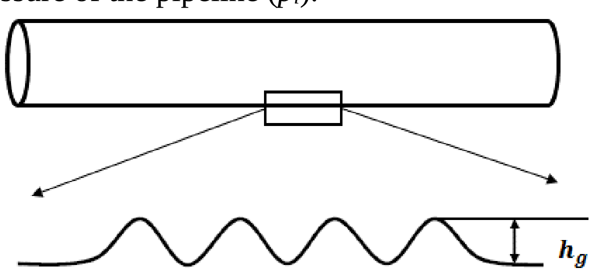

Figure 5-4 Pipe geometry imperfection

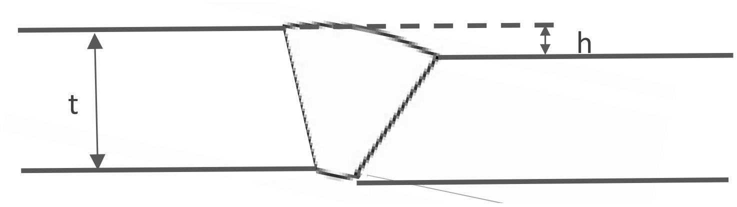

Figure 5-5 Weld high-low misalignment

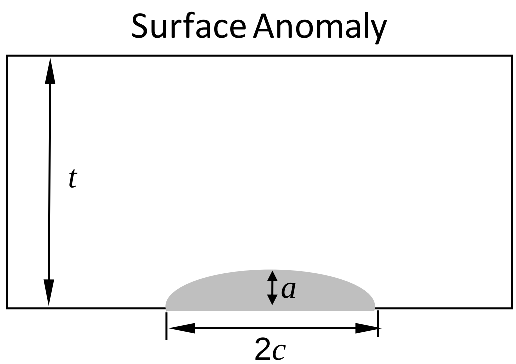

Figure 5-6 Dimension of girth weld planar anomaly

5.5 Assessment of Tensile Strain Capacity of Pipe Segments with Girth Welds

5.5.1 Overview

The procedures given in this section determine the tensile strain capacity (i.e., resistance to tensile rupture) of a pipe girth weld subjected to bending deformation and/or axial tension. These procedures were developed based on the studies presented in Section 4.2 of the PHMSA project report [1].

The tensile strain capacity corresponds to a service limit state. If the tensile strain capacity (with safety factor) is exceeded, repair is needed. Two different levels of assessment procedures are provided. The Level I procedures (Section 5.5.4) consist of easy-to-use graphics and equations. The Level II procedures (Section 5.5.5) are case-specific finite element analyses. The Level I procedures are based on certain conservative assumptions and have limited applicable range. If the Level I procedures are not applicable or the Level I assessment results become too restrictive, the Level II procedures can be used.

5.5.2 Definition of Tensile Strain Capacity

The tensile strain capacity of a girth weld is the maximum tensile strain that the girth weld can withstand before any leak or rupture. In the guidelines, the tensile strain capacity is designated to capture the overall capacity of the girth weld to accommodate global/nominal longitudinal deformation.

In order to properly represent the nominal strain, the tensile strain capacity was obtained under longitudinal tension and was measured in such a way that the reported tensile strain capacity was not affected by the strain concentration near the girth weld defects. It is known that the tensile strain capacity of a pipe under longitudinal tension is lower than that under bending. Therefore, the tensile strain capacity given in the guidelines can be used for bending deformation conservatively.

For a regular girth weld, the material properties and wall thicknesses of the two pipes on the different sides of the girth weld are assumed to be the same. The tensile strain capacity can be obtained from either pipe. For a transition weld, the material properties and wall thicknesses of the two pipes on the different sides of the girth weld are different. Therefore, the tensile strain capacities obtained from the two pipes are different. The tensile strain capacity given by this guideline is obtained from thin pipe.

The pipe integrity is usually determined by comparing strain capacity with strain demand. To properly use the strain capacity determined by the guidelines, consistency between the measures of strain demand and strain capacity must be assured. Otherwise, the assessment results may become either overly conservative or not conservative.

The longitudinal strain demand should be obtained during operations. The strain demand can be measured by IMU tools or calculated from numerical simulations (e.g., finite element analyses of pipe-soil interactions). For transition welds, the strain demand should be measured in the thin pipe.

For most IMU measurements, the reported strain demand is the average strain in a 10-ft gauge length. Since the area of the strain concentration induced by the girth weld defects is much smaller than the 10-ft gauge length, the IMU strain is close to the nominal strain demand and can be directly compared with the strain capacity in the guidelines. It should be noted that the IMU tools measure only bending strain. The membrane/cable tensile strain due to other effects such as the temperature effect and the elongation of a bent pipe should be estimated and added to the measured IMU strain.

For most strain demand numerical simulations, the girth weld defects are not built in the numerical models. For such circumstances, the strain demand calculated by the numerical simulations does not capture the strain concentration induced by the girth weld defects. As a result, the calculated strain demand from the numerical simulations can be directly compared with the strain capacity in the guidelines.

5.5.3 Determine the Required Parameters

1) STEP 1 – Determine the pipe outside diameter (D) and wall thickness (t). For a transition weld jointing unequal wall pipes, the wall thicknesses of both the thick-wall pipe (t_{thick}), and the thin-wall pipe (t_{thin}) need to be determined. The nominal pipe outside diameter and wall thickness should be used.
2) STEP 2 – Determine the operating pressure (p_i). The maximum pressure during normal operation should be used. If the actual operating pressure is not available, the maximum allowable operating pressure (MAOP) should be used.
3) STEP 3 – Determine the pipe yield-to-tensile strength ratio (R_{YT}), i.e., Y/T ratio. Determine the longitudinal upper bound pipe Y/T ratio following Step 3 of Section 3.6.3. For transition welds, the R_{YT} of the thin-wall pipe should be used (R_{YT}^{thin}).
4) STEP 4 – Determine the pipe yield and ultimate tensile strengths. For regular girth welds, determine the upper-bound pipe yield (σ_y) and ultimate tensile (σ_u) strengths in the longitudinal direction. For transition welds, determine (1) the lower-bound pipe yield (σ_y^{thick}) and ultimate tensile (σ_u^{thick}) strengths of the thick-wall pipe in the longitudinal direction and (2) the upper-bound pipe yield (σ_y^{thin}) and ultimate tensile (σ_u^{thin}) strengths

of the thin-wall pipe in the longitudinal direction. Procedures similar to those in Step 4 of Sections 3.6.3 and 3.7.3 can be followed to determine lower-bound and upper-bound pipe strengths, respectively.

5) STEP 5 – Determine the weld ultimate tensile strength (σ_u^w). The lower bound ultimate tensile strength of the weld should be used.
6) STEP 6 – Determine the depth (a) and length ($2c$) of the planar anomaly. The depth (a) and length ($2c$) should be determined using the procedures in Section 9.3.6 of API 579 [4].
7) STEP 7 – Determine the high-low misalignment (h) of the girth weld. The maximum high-low misalignment along the length of the anomaly should be used.
8) STEP 8 – Determine the apparent toughness (δ_A) of the girth weld. The lower bound apparent toughness should be used. The apparent toughness (δ_A) should be determined using the procedures in Section 8.4 of the PMHSA strain-based design report [5]
9) STEP 9 – Calculate the weld strength mismatch ratio (R_M) measured by ultimate tensile strength: $R_M = \dfrac{\sigma_u^w}{\sigma_u}$ (for regular girth welds); $R_M = \dfrac{\sigma_u^w}{\sigma_u^{thin}}$ (for transition welds).
10) STEP 10 (for transition welds only) – Calculate the flow stress of the thin pipe (σ_f^{thin}):

$$\sigma_f^{thin} = \frac{\sigma_y^{thin} + \sigma_u^{thin}}{2}.$$

11) STEP 11 (for transition welds only) – Calculate the grade ratio (R_G), the yield strength ratio (R_y), and the ultimate tensile strength ratio (R_u) of the two pipes joined by the transition weld: $R_G = \dfrac{\sigma_{SMYS}^{thin}}{\sigma_{SMYS}^{thick}}$, $R_y = \dfrac{\sigma_y^{thin}}{\sigma_y^{thick}}$, and $R_u = \dfrac{\sigma_u^{thin}}{\sigma_u^{thick}}$.
12) STEP 12 (for transition welds only) – Calculate the wall thickness ratio (R_t) of the two pipes joined by the transition weld: $R_t = \dfrac{t_{thick}}{t_{thin}}$.
13) STEP 13 – Calculate the normalized high-low misalignment (R_h): $R_h = \dfrac{h}{t}$ (for regular welds); $R_h = \dfrac{h}{t_{thin}}$ (for transition welds);
14) STEP 14 – Calculate the normalized depth (R_a) and normalized length (R_c) of the planar anomaly: $R_a = \dfrac{a}{t}$, $R_c = \dfrac{2c}{t}$ (for regular welds); $R_a = \dfrac{a}{t_{thin}}$, $R_c = \dfrac{2c}{t_{thin}}$ (for transition welds);

15) STEP 15 – Calculate pressure factor (f_p): $f_p = \frac{p_i D}{2t\sigma_{SMYS}}$ (for regular welds);

$f_p = \frac{p_i D}{2t_{thin}\sigma_{SMYS}^{thin}}$ (for transition welds).

16) STEP 16 – Confirm the applicable range for Level I assessment procedures. Proceed to Section 5.5.4 if all the following conditions are satisfied. Proceed to Section 5.5.5 if any of the following conditions is not satisfied.

<u>Conditions for all girth welds:</u>

$0.05 \le R_a \le 0.50$,

$1.0 \le R_c \le 20$,

$R_h \le 0.2$,

$f_p \le 0.8$,

0.2 mm (0.0079 in) $\le \delta_A \le$ 2.5 mm (0.10 in),

12.7 mm (0.5 in) $\le t \le$ 25.4 mm (1.0 in),

$0.75 \le R_{YT} \le 0.94$, and

$1.0 \le R_M \le 1.3$.

<u>Additional conditions for counterbore-tapered girth welds</u>

$\sigma_y^{thick} \ge \sigma_y^{thin}$, and

$\sigma_u^{thick} \ge \sigma_u^{thin}$.

<u>Additional conditions for back-beveled girth welds</u>

$0.75 \le R_{YT} \le 0.92$,

$1.00 \le R_M \le 1.15$,

$1.00 \le R_y \le 1.25$,

$\sigma_u^{thick} \ge \sigma_f^{thin}$, and

$R_t \ge \max\left(R_G, R_u, R_y\right)$.

5.5.4 Assessment Procedures (Level I)

5.5.4.1 <u>Regular Girth Welds</u>

1) STEP 1 – Determine the tensile strain capacity (ε_t^{crit}) of the regular girth weld without a safety factor using the equations given in Appendix A [5].

2) STEP 2 – The tensile strain capacity ($\varepsilon_{t,gw}^{crit}$) of the regular girth weld with a safety factor can be determined as

$$\varepsilon_{t,gw}^{crit} = \gamma_{t,gw}\varepsilon_{t}^{crit} , \tag{5-1}$$

where, $\gamma_{t,gw}$ is the safety factor applied to the tensile strain capacity of a regular girth weld. The recommended safety factor is $\gamma_{t,gw} \leq 0.60$. The units of ε_{t}^{crit} and $\varepsilon_{t,gw}^{crit}$ calculated from the above equations are mm/mm (in/in). For example, if the tensile strain capacity is 2.0% (i.e., 0.02 mm/mm or in/in), the calculated ε_{t}^{crit} or $\varepsilon_{t,gw}^{crit}$ is 0.02.

5.5.4.2 <u>Transition Girth Welds – Counterbore Tapered</u>

1) STEP 1 – Determine the tensile strain capacity (ε_{t}^{crit}) of the corresponding regular girth weld without a safety factor using the equations given in Appendix A [5]. The input parameters should be determined from the thin-wall pipe.
2) STEP 2 – Calculate the tensile strain capacity ($\varepsilon_{t,tw}^{crit}$) of the counterbore-tapered weld with a safety factor using the following equation

$$\varepsilon_{t,tw}^{crit} = \gamma_{t,tw}\varepsilon_{t}^{crit} , \tag{5-2}$$

where, $\gamma_{t,tw}$ is the safety factor applied to the tensile strain capacity of a transition girth weld. The recommended safety factor is $\gamma_{t,tw} \leq 0.60$. The units of ε_{t}^{crit} and $\varepsilon_{t,tw}^{crit}$ calculated from the above equations are mm/mm (in/in). For example, if the tensile strain capacity is 2.0% (i.e., 0.02 mm/mm or in/in), the calculated ε_{t}^{crit} or $\varepsilon_{t,tw}^{crit}$ is 0.02.

5.5.4.3 <u>Transition Girth Welds – Back-Beveled</u>

1) STEP 1 – Determine the tensile strain capacity (ε_{t}^{crit}) of the corresponding regular girth weld without a safety factor using the equations given in Appendix A [5]. The input parameters should be determined from the thin-wall pipe.
2) STEP 2 – Calculate the tensile strain capacity ($\varepsilon_{t,tw}^{crit}$) of the back-beveled weld with a safety factor using the following equations:

$$\varepsilon_{t,tw}^{crit} = \gamma_{t,tw}\varepsilon_{t}^{crit}\left(1 - F_{tw}\right), \tag{5-3}$$

$$F_{tw} = 0.1443 \cdot \left[\max\left(1.0, R_{y}\right) - 1\right]^{0.4241}\left(100 \cdot \varepsilon_{t}^{ref} + 3.053\right), \tag{5-4}$$

where, $\gamma_{t,tw}$ is the safety factor applied to the tensile strain capacity of a transition girth weld. The recommended safety factor is $\gamma_{t,tw} \leq 0.60$. ε_t^{ref} (unit: mm/mm or in/in) is the TSC of the corresponding regular girth weld for $\delta_A = 0.8$ mm, i.e., $\varepsilon_t^{ref} = \varepsilon_t^{crit}\big|_{\delta_A = 0.8\text{ mm}}$. $\varepsilon_t^{crit}\big|_{\delta_A = 0.8\text{ mm}}$ should be calculated from the equations given in

Appendix A [5], in which all the input parameters should be determined from the thin-wall pipe.

5.5.5 Assessment Procedures (Level II)

5.5.5.1 General Requirement on the Models

For the Level II assessment, case-specific finite element analyses (FEA) are required. Three-dimension solid (brick) elements are recommended to capture the shape of the weld and planar anomaly. Adequate mesh refinement (i.e., proper element size) should be determined through mesh convergence studies. The length of the pipe model should be kept long enough to obtain a uniform strain zone (Figure 5-8), i.e., the strain in the uniform strain zone should not be affected by the strain concentration in the weld area and the boundary conditions applied at the pipe ends.

5.5.5.2 Determination of Input Parameters

The input parameters of the FEA models (e.g., pipe geometries, material properties, etc.) can be determined using the following recommendations:

1) The nominal pipe outside diameter and wall thickness should be used.
2) Modeling the weld with its actual profile, including weld passes, weld cap, and HAZ, is preferred.
3) The longitudinal tensile stress-strain curve of the actual pipe joint showing lower-bound strain hardening capacity (i.e., upper-bound pipe Y/T ratio) should be used. If the actual stress-strain curve is not available, the stress-strain curve can be constructed following the procedures given in Section 6.1 of the PHMSA project report [5] using the pipe Y/T ratio and yield strength. The pipe Y/T ratio and yield strength can be determined following STEPs 3 and 4 in Section 5.5.3, respectively.
4) The lower-bound longitudinal tensile stress-strain curve of the girth weld should be used. If the actual stress-strain curve is not available, the stress-strain curve can be constructed following the procedures given in Section 6.1 of the PHMSA project report [5] using the lower-bound weld ultimate tensile strength. The circumferential properties can be used if the longitudinal properties are not available.

5.5.5.3 Loading and Results

The recommended loading steps for the FEA are given in the following:

1) STEP 1 - Keep longitudinal load free and apply internal pressure to reach the maximum allowable operating pressure (MAOP); and
2) STEP 2 - Keep the internal pressure at MAOP, fix the displacement of one pipe end and apply uni-axial tensile displacement to the other end until the maximum longitudinal load (i.e., the reaction force at the node where the displacement is applied) is reached.

The tensile strain capacity is the longitudinal tensile strain when the crack tip opening displacement (δ_F) reaches the apparent toughness (δ_A). The crack tip opening displacement (δ_F) should be measured from the deformed anomaly profile at the deepest point along the anomaly front following the traditional 90°-line method as shown in Figure 5-7.

The longitudinal tensile strain should be measured as the average strain within a finite gauge length ($l_0 \geq D$) in the area away from the weld and pipe ends as shown in Figure 5-8. The strain measured at the 12 o'clock position should be used (assuming the planer anomaly is centered at the 12 o'clock position). For transition welds, the longitudinal tensile strain should be measured on the thin-wall pipe.

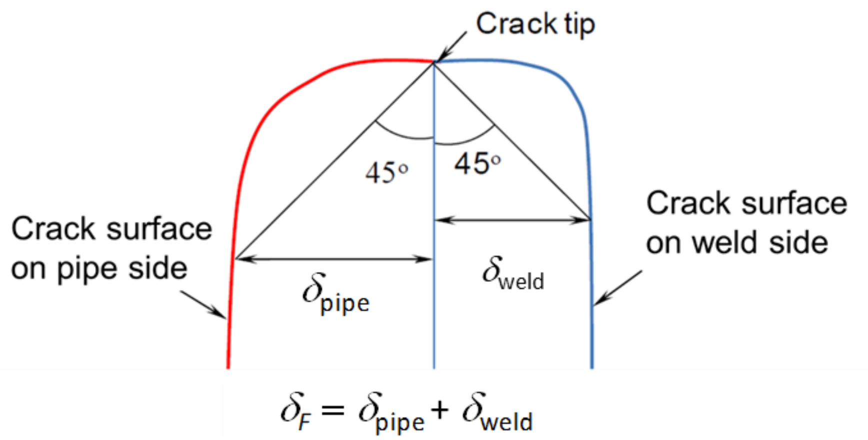

Figure 5-7 Schematic of δ_F measurement

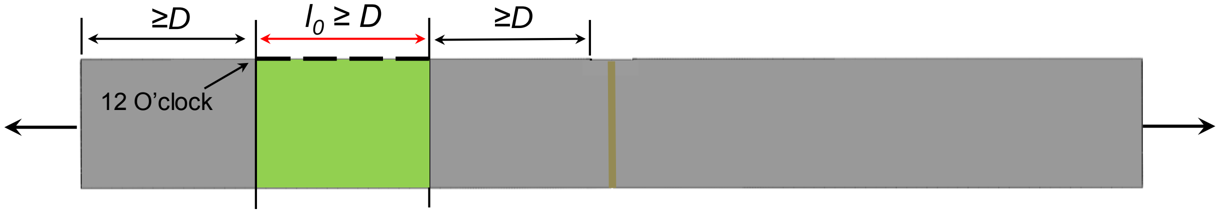

Figure 5-8 Calculation of tensile strain capacity

5.6 Assessment of Compressive Strain Capacity of Pipe Segments with Girth Welds

5.6.1 Overview

The procedures in this section determine the compressive strain capacity (i.e., resistance to compressive buckling) of a pipe girth weld subjected to bending-dominant deformation. The procedures are not applicable for pipes subjected to pure axial compression. These procedures were developed based on the studies presented in Section 4.3 of the PHMSA project report [1].

The compressive strain capacity defined in the guidelines corresponds to a service limit state. If the compressive strain capacity (with safety factor) is exceeded, post-wrinkle assessment [8] can be conducted to determine if repair is needed. Two different levels of assessment procedures are provided. The Level I procedures (Section 5.6.4) consist of easy-to-use equations. The Level II procedures (Section 5.6.5) are case-specific finite element analyses. The Level I procedures are based on certain conservative assumptions and have limited applicable range. If the Level I procedures are not applicable or the Level I assessment results become too restrictive, the Level II procedures can be used.

The assessment equations given in the Level I procedures are in the form of add-on equations to the compressive strain models developed in a prior PHMSA sponsored project [9]. The girth weld is treated as an equivalent geometry imperfection.

5.6.2 Definition of Compressive Strain Capacity

In the guidelines, the compressive strain capacity (CSC) is defined as the compressive strain corresponding to the maximum bending moment that a pipe girth weld can withstand. Since small wrinkles can be formed in the pipe when the bending moment reaches the maximum value, strain localization can be found near the wrinkle.

For regular girth welds, two methods are used in the guidelines to measure the compressive strain capacity (CSC), i.e., 2D CSC ($\varepsilon_{c,gw}^{crit,2D}$) and CSC by extrapolation ($\varepsilon_{c,gw}^{crit,ex}$). The 2D CSC ($\varepsilon_{c,gw}^{crit,2D}$) follows the traditional definition of the CSC used for plain pipes, i.e., the average compressive strain within a 2*D* (*D* is the pipe outside diameter) gauge length centered at the wrinkle location. The 2D CSC is affected by the strain localization at the wrinkle.

The CSC by extrapolation ($\varepsilon_{c,gw}^{crit,ex}$) is the strain determined in such a way that the reported CSC is not affected by the strain localization at the wrinkle. The CSC by extrapolation is designated to capture the overall capacity of the girth weld to accommodate global/nominal longitudinal bending deformation.

For transition welds, most of the compressive strain is generated in the thin-wall pipe, the compressive strain capacity of the transition weld is defined by using the compressive strain in the thin-wall pipe. Similar to the CSC of regular girth welds, two CSC definitions are used for transition welds: (1DS) CSC ($\varepsilon_{c,tw}^{crit,1DS}$) and CSC by extrapolation ($\varepsilon_{c,tw}^{crit,ex}$). The definition of the 1D single side (1DS) CSC ($\varepsilon_{c,tw}^{crit,1DS}$) of the transition weld is equivalent to that of the 2D CSC ($\varepsilon_{c,gw}^{crit,2D}$) of the regular weld. The 1DS CSC ($\varepsilon_{c,tw}^{crit,1DS}$) is measured by the average compressive strain within a 1*D* gauge length with one end of the gauge at the center of the wrinkle and the other end 1*D* away in the thin-wall pipe.

All the CSC mentioned in the above were obtained under bending. It is known that the CSC of a pipe under longitudinal compression is lower than that under bending. Therefore, the CSC given in the guidelines is applicable only for bending-dominant deformation.

The pipe integrity is usually determined by comparing strain capacity with strain demand. To properly use the strain capacity determined by the guidelines, consistency between the measures of strain demand and strain capacity must be assured. Otherwise, the assessment results may become either overly conservative or not conservative.

The longitudinal strain demand should be obtained during operations. The strain demand can be measured by IMU tools or calculated from numerical simulations (e.g., finite element analyses of pipe-soil interactions). For transition welds, the strain demand should be measured in the thin pipe.

For most IMU measurements, the reported strain demand is the average strain in a 10-ft gauge length. The 10-ft gauge length is typically much greater than 2*D* and much greater than the area of strain concentration induced by the wrinkle. For such circumstances, the strain demand is close to the nominal strain and therefore, the CSC by extrapolation ($\varepsilon_{c,gw}^{crit,ex}$ or $\varepsilon_{c,tw}^{crit,ex}$) should be used. If the reported strain demand is measured with a gauge length equal to or less than 2D, the 2D CSC ($\varepsilon_{c,gw}^{crit,2D}$) or (1DS) CSC ($\varepsilon_{c,tw}^{crit,1DS}$) can be used. It should be noted that the IMU tools measure only bending strain. The membrane compressive strain due to other effects such as the temperature effect should be estimated and added to the measured IMU strain.

For most of strain demand numerical simulations, beam-type elements are used and wrinkle formation is not allowed. Therefore, the strain demand calculated by such numerical simulations does not capture the strain concentration induced by wrinkles. For such circumstances, the CSC by extrapolation ($\varepsilon_{c,gw}^{crit,ex}$ or $\varepsilon_{c,tw}^{crit,ex}$) should be used.

5.6.3 Determine the Required Parameters

1) STEP 1 – Determine the pipe outside diameter (D) and wall thickness (t). The nominal pipe outside diameter and wall thickness should be used. For a transition weld jointing unequal wall pipes, the wall thickness of both the thick-wall pipe (t_{thick}) and the thin-wall pipe (t_{thin}) need to be determined.
2) STEP 2 – Determine the pipe manufacturing geometry imperfection (h_g). The maximum geometry imperfection height (from peak to valley as shown in Figure 5-4) of the actual pipe should be used. If the h_g is not available, the following values can be used:

   $h_g = 0.08t$ for pipes manufactured with expansion procedures (e.g., UOE); and

   $h_g = 0.04t$ for pipes manufactured without expansion procedures.

   For transition welds, the h_g of the thin wall pipe should be used.
3) STEP 3 – Calculate the normalized geometry imperfection height: h_g/t (for regular girth welds); h_g/t_{thin} (for transition welds).
4) STEP 4 – Determine the high-low misalignment (h) of girth welds. The maximum high-low misalignment along the length of the girth weld should be used.
5) STEP 5 – Calculate the normalized high-low misalignment (R_h): $R_h = h/t$ (for regular girth welds); $R_h = h/t_{thin}$ (for transition welds).
6) STEP 6 – Determine the operating pressure (p_i). The lower-bound pressure during normal operation should be used.
7) STEP 7 – Determine the pipe yield-to-tensile strength ratio (R_{YT}), i.e., Y/T ratio. Determine the longitudinal upper bound pipe Y/T ratio following Step 3 of Section 3.6.3. For transition welds, the R_{YT} of the thin-wall pipe should be used (R_{YT}^{thin}).
8) STEP 8 – Determine the pipe yield strength (σ_y). Determine the upper-bound pipe yield strength following Step 4 in Section 3.7.3. For transition welds, the yield strength of the thin-wall pipe should be used.

9) STEP 9 – Calculate pressure factor (f_p): $f_p = P_i D/(2t\sigma_y)$ (for regular girth welds); $f_p = P_i D/(2t_{thin}\sigma_y)$ (for transition welds).

10) STEP 10 – Confirm the applicable range for Level I assessment procedures. Proceed to Section 5.6.4 if all the following conditions are satisfied. Proceed to Section 5.6.5 if any of the following conditions is not satisfied.

    Regular Girth Welds

    $20 \le D/t \le 104$,

    $0.0 \le f_p \le 0.80$,

    $0.70 \le R_{YT} \le 0.96$,

    $0.01 \le h_g/t \le 0.30$,

    $\varepsilon_e(\%) \le 2.0$,

    $0 \le f_n \le 0.40$, and

    $R_h < 0.5$.

    Transition Girth Welds

    $51 \le D/t \le 72$,

    $0.0 \le f_p \le 0.72$,

    $0.77 \le R_{YT} \le 0.88$,

    $0.01 \le h_g/t \le 0.30$,

    $\varepsilon_e(\%) \le 2.0$,

    $0 \le f_n \le 0.40$, and

    $R_h < 0.5$.

5.6.4 Assessment Procedures (Level I)

5.6.4.1 Regular Girth Welds

1) STEP 1 – Determine the normalized equivalent geometry imperfection height (h_g^e/t) of regular girth welds using the following equations:

$$h_g^e/t = max\left(h_g/t\,, 0.04\right) \tag{5-5}$$

2) STEP 2 – Calculate the CSC ($\varepsilon_c^{crit,2D}$) without safety factor with the CSC equations given in Appendix B [9] by replacing the normalized geometry imperfection height (h_g/t) with the normalized equivalent geometry imperfection height (h_g^e/t) calculated in STEP 1, i.e., Eq. (5-5).

3) STEP 3 – The 2D CSC with a safety factor ($\varepsilon_{c,gw}^{crit,2D}$) can be determined as

$$\varepsilon_{c,gw}^{crit,2D} = \gamma_c \varepsilon_c^{crit,2D}, \tag{5-6}$$

where, γ_c is the safety factor applied to the CSC. The recommended safety factor is $\gamma_c \leq 0.80$. The units of $\varepsilon_c^{crit,2D}$ and $\varepsilon_{c,gw}^{crit,2D}$ calculated from the above equations are %. For example, if the CSC is 2.0% (i.e., 0.02 mm/mm or in/in), the calculated $\varepsilon_c^{crit,2D}$ or $\varepsilon_{c,gw}^{crit,2D}$ is 2.0.

4) STEP 4 – Calculate the CSC by extrapolation ($\varepsilon_{c,gw}^{crit,ex}$) with the following equation,

$$\varepsilon_{c,gw}^{crit,ex} = 1.03 * \varepsilon_{c,gw}^{crit,2D} - 0.20 \tag{5-7}$$

The units of $\varepsilon_{c,gw}^{crit,ex}$ and $\varepsilon_{c,gw}^{crit,2D}$ calculated from the above equations are %.

5.6.4.2 Transition Welds

1) STEP 1 – Determine the normalized equivalent geometry imperfection height (h_g^e/t) of transition welds using the following equation:

$$h_g^e/t_{thin} = 1.70 * \left(h_g/t_{thin}\right) + 0.13 \tag{5-8}$$

where the h_g/t_{thin} and h_g^e/t_{thin} are in the unit of mm/mm (in/in).

2) STEP 2 – Calculate the CSC ($\varepsilon_c^{crit,2D}$) without safety factor with the CSC equations given in Appendix B [9] by replacing the normalized geometry imperfection height (h_g/t) with the normalized equivalent geometry imperfection height (h_g^e/t_{thin}) calculated in STEP 1, i.e., Eq. (5-8).

3) STEP 3 – The 1DS CSC ($\varepsilon_{c,tw}^{crit,1DS}$) with a safety factor can be determined as

$$\varepsilon_{c,tw}^{crit,1DS} = \gamma_c \varepsilon_c^{crit,2D}, \tag{5-9}$$

where, γ_c is the safety factor applied to the CSC. The recommended safety factor is $\gamma_c \leq 0.80$. The units of $\varepsilon_c^{crit,2D}$ and $\varepsilon_{c,tw}^{crit,1DS}$ calculated from the above equations are %. For example, if the CSC is 2.0% (i.e., 0.02 mm/mm or in/in), the calculated $\varepsilon_c^{crit,2D}$ or $\varepsilon_{c,tw}^{crit,1DS}$ is 2.0.

4) STEP 4 – Calculate the CSC by extrapolation ($\varepsilon_{c,tw}^{crit,ex}$) with the following equation,

$$\varepsilon_{c,tw}^{crit,ex} = 1.03 * \varepsilon_{c,tw}^{crit,1DS} - 0.20 \tag{5-10}$$

The units of $\varepsilon_{c,tw}^{crit,ex}$ and $\varepsilon_{c,tw}^{crit,1DS}$ calculated from the above equations are %.

5.6.5 Assessment Procedures (Level II)

5.6.5.1 General Requirement on the Models

For the Level II assessment, case-specific finite element analyses (FEA) are required. Three-dimensional solid (brick) elements are recommended to model the pipe and capture the profile of the girth weld. Adequate mesh refinement (i.e., proper element size) should be determined through mesh convergence studies. The length of the pipe model should be kept long enough so that there exists a remote strain zone of at least 1*D* long between the girth weld and pipe ends, in which the strain is not affected by the strain concentration occurred at either the girth weld or the pipe ends.

5.6.5.2 Determination of Input Parameters

The input parameters of the FEA models (e.g., pipe geometries, material properties, etc.) can be determined using the following recommendations:

1) The nominal pipe outside diameter and wall thickness should be used.
2) Modeling the weld with its actual profile, including weld passes, weld cap, and HAZ, is preferred.
3) The longitudinal tensile stress-strain curve of the actual pipe joint showing lower-bound strain hardening capacity (i.e., upper-bound pipe Y/T ratio) should be used. If the actual stress-strain curve is not available, the stress-strain curve can be constructed following the procedures given in Section 6.1 of the PHMSA project report [5] using the pipe Y/T ratio and yield strength. The pipe Y/T ratio and yield strength can be determined following STEPs 7 and 8 in Section 5.6.3, respectively.

5.6.5.3 Loading Steps

The recommended loading steps for the FEA are given in the following:

1) STEP 1 – Keep longitudinal load free and apply internal pressure to reach the lower-bound pressure during normal operation; and
2) STEP 2 – Keep the internal pressure at the lower bound pressure in normal operation, for regular girth welds, apply rotation at both ends of the pipe to bend the pipe until the maximum bending moment is reached; for transition welds, fix the displacement of the thick-wall pipe end and apply rotation at the thin-wall pipe end to bend the pipe until the maximum bending moment is reached.

5.6.5.4 Calculation of CSC

The compressive strain capacity is the longitudinal compressive strain corresponding to the maximum bending moment. The bending moment need to be measured at the pipe cross section at the center of the wrinkle. The procedures for calculating the 2D CSC ($\varepsilon_{c,gw}^{crit,2D}$) and CSC by extrapolation ($\varepsilon_{c,gw}^{crit,ex}$) are given below.

5.6.5.4.1 *Regular Girth Welds*

1) 2D CSC ($\varepsilon_{c,gw}^{crit,2D}$)

   The procedures for calculating the 2D CSC ($\varepsilon_{c,gw}^{crit,2D}$) of the regular girth welds are the same as those for calculating the 2D CSC ($\varepsilon_{c,dent}^{crit,2D}$) of pipes with dents as shown in Section 4.5.5.4.

2) CSC by Extrapolation ($\varepsilon_{c,gw}^{crit,ex}$)

   The procedures for calculating the CSC by extrapolation ($\varepsilon_{c,gw}^{crit,ex}$) of the regular girth welds are the same as those for calculating the CSC by extrapolation ($\varepsilon_{c,dent}^{crit,ex}$) of pipes with dents as shown in Section 4.5.5.4. The calculation of the CSC by extrapolation ($\varepsilon_{c,gw}^{crit,ex}$) of the regular girth welds is shown in Figure 5-9.

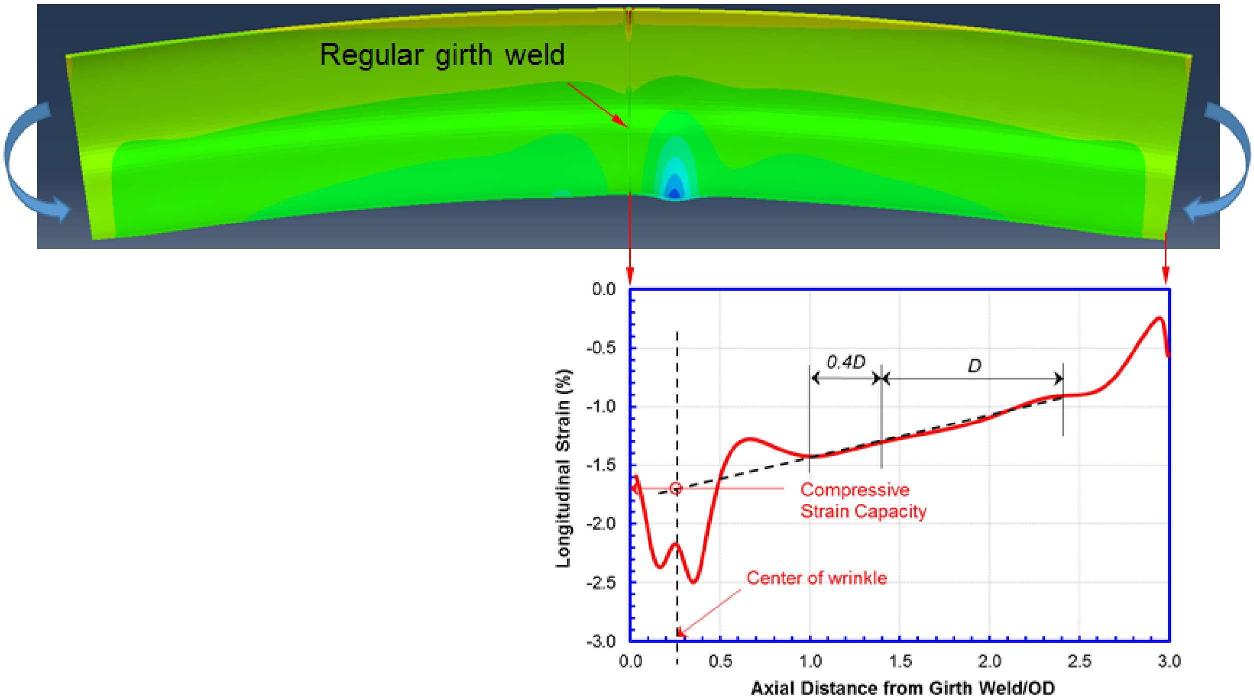

Figure 5-9 Calculation of CSC by extrapolation for regular girth weld

5.6.5.4.2 *Transition Welds*

1) 1DS CSC ($\varepsilon_{c,tw}^{crit,1DS}$)

For the transition welds, since most strain is found in the thin-wall pipe, the local CSC is defined using the strain in the thin pipe. Equivalent to the 2D CSC ($\varepsilon_{c,gw}^{crit,2D}$) of the regular girth welds, the local CSC of the transition welds is measured as the average compressive strain within a $1D$ gauge length with one end of the gauge at the center of the wrinkle and the other end $1D$ away in the thin-wall pipe, as shown in Figure 5-10. The local CSC of the transition welds is referred to as the 1D single-side CSC, i.e., 1DS CSC ($\varepsilon_{c,tw}^{crit,1DS}$). The 1DS CSC ($\varepsilon_{c,tw}^{crit,1DS}$) should be calculated using the following equation:

$$\varepsilon_{c,tw}^{crit,1DS} = \varepsilon_t - D * (\theta_2 - \theta_1)/l_0 \quad (5\text{-}11)$$

where ε_t is the tensile strain on the tensile side of the pipe, θ_1 and θ_2 are the rotation angles (in unit of rad) of the pipe cross sections at the end of the gauge length, l_0 (= $1D$) is the gauge length, and D is the pipe outer diameter.

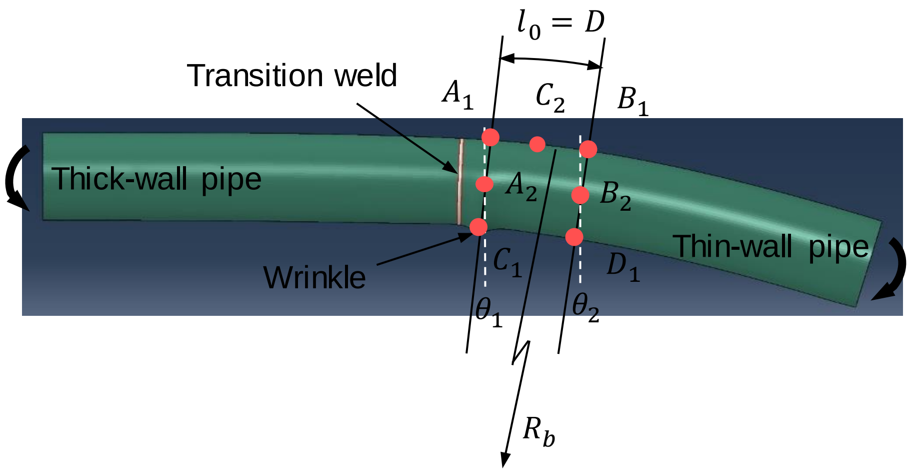

Figure 5-10 Calculation of 1DS CSC for transition welds

Depending on the method used to determine the tensile strain (ε_t) and the rotation angles (θ_1, θ_2), the 1DS CSC ($\varepsilon_{c,tw}^{crit,1DS}$) can be calculated with one of the methods given below.

- Method 1 (Option 1):

  The tensile strain (ε_t) is calculated as the average strain within the gauge length on the tensile side of the pipe by assuming the deformed pipe is a part of a circle with the radius of R_b, as shown in Figure 5-10. The radius (R_b) and rotation angles (θ_1 and θ_2) are determined using the coordinates of the four points (A_1, B_1, C_1 and D_1) as shown in Figure 5-10. The tensile strain (ε_t) is calculated by the following equation:

  $$\varepsilon_t = R_b * (\theta_2 - \theta_1)/l_0 - 1 \qquad (5\text{-}12)$$

- Method 1 (Option 2):

  The tensile strain (ε_t) is determined as the strain at the center of the gauge (Point C_2) on the tension side of the pipe, as shown in Figure 5-10. The rotation angles (θ_1 and θ_2) are measured at the middle height of the pipe (Points A_2 and B_2), as shown in Figure 5-10.

- Method 2:

  The 1DS CSC ($\varepsilon_{c,tw}^{crit,1DS}$) is directly calculated using the displacement of two points (one at the center of the wrinkle and the other is $1D$ away in the thin pipe) on the bottom side of the pipe (Points C_1 and D_1), as shown in Figure 5-10.

3) CSC by Extrapolation ($\varepsilon_{c,tw}^{crit,ex}$)

   The CSC by extrapolation ($\varepsilon_{c,tw}^{crit,ex}$) is determined from the strain distribution in the remote strain zone in the thin-wall pipe by extrapolating the strain along the outmost compressive fiber of the thin-wall pipe to the wrinkle location (Figure 5-11). The remote strain zone is one pipe diameter (D) wide and $0.4D$ away from the last strain valley from the center of the wrinkle.

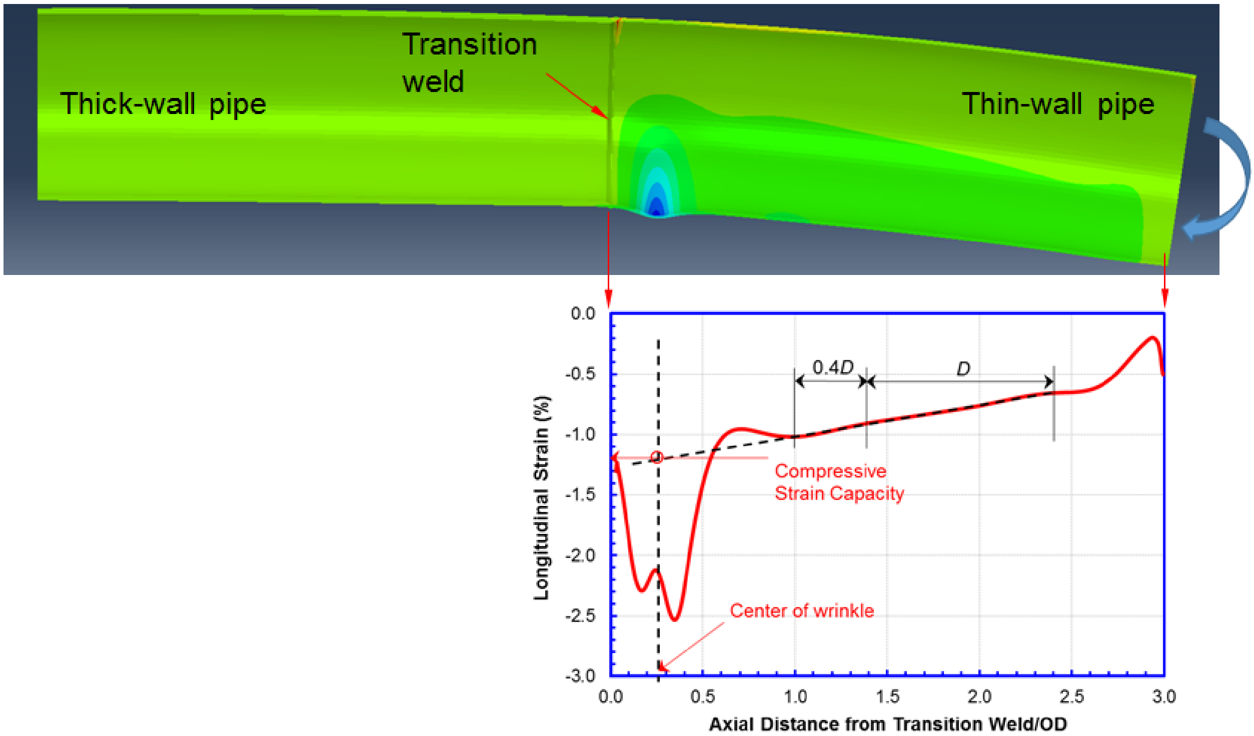

Figure 5-11 Calculation of CSC by extrapolation for transition welds

6 Nomenclature

6.1 Abbreviations

CSC	Compressive strain capacity
FCAW	Flux-cored arc welding
FEA	Finite element analyses
GMAW	Gas metal arc welding
HAZ	Heat affected zone
IMU	Inertial Mapping Unit
MAOP	Maximum allowable operating pressure
SBD	Strain-based design
SBDA	Strain-based design and assessment
SMAW	Shielded metal arc welding
SMYS	Specified minimum yield strength
SMTS	Specified minimum tensile strength
TSC	Tensile strain capacity

6.2 Symbols

A_c^l	Area of the longitudinal river bottom profile of corrosion
A_c^h	Area of the circumferential river bottom profile of corrosion
a	Depth of planar flaw
c	Half length of planar flaw
d_c	Depth of corrosion anomaly
d_{dp}	Depth of the dent under internal pressure
D	Pipe outside diameter (OD)
f_n	Net-section stress factor
f_p	Pressure factor
h	Girth weld high-low misalignment
h_g	Height of pipe geometry imperfection
h_g^e	Height of equivalent pipe geometry imperfection for dents and transition welds
L	Counterbore length of transition girth weld
L_c	Length of a corrosion anomaly in pipe longitudinal direction
l_0	Gauge length for strain measurement
P_b	Burst pressure of pipes without longitudinal strain
$P_b^{\varepsilon_c}$	Burst pressure of pipes under longitudinal compressive strain

p_i	Internal pressure
R_a or η	Normalized depth of crack-like planar anomalies, i.e., a/t
R_b	Pipe bending radius
R_c or β	Normalized length of crack-like planar anomalies, i.e., $2c/t$
R_G	Pipe SMYS ratio between the thin-wall pipe and the thick-wall pipe jointed by a transition weld, i.e., $\sigma_{SMYS}^{thin}/\sigma_{SMYS}^{thick}$
R_h or ψ	Normalized weld high-low misalignment, i.e., h/t
R_M or ϕ	Weld metal strength mismatch ratio, i.e., σ_u^w / σ_u
R_t	Wall thickness ratio between the thick-wall pipe and the thin-wall pipe jointed by a transition weld, i.e., t_{thick}/t_{thin}
R_u	Pipe ultimate tensile strength ratio between the thin-wall pipe and the thick-wall pipe jointed by a transition weld, i.e., $\sigma_u^{thin}/\sigma_u^{thick}$
R_y	Pipe yield strength ratio between the thin-wall pipe and the thick-wall pipe jointed by a transition weld, i.e., $\sigma_y^{thin}/\sigma_y^{thick}$
R_{YT} or ξ	Pipe yield to tensile strength ratio, or Y/T ratio, i.e., σ_y / σ_u
R_{YT}^{thin}	Pipe yield to tensile strength ratio, or Y/T ratio, of the thin-wall pipe jointed by a transition weld
t	Pipe wall thickness
t_{thick}	Wall thickness of the thick-wall pipe jointed by a transition weld
t_{thin}	Wall thickness of the thin-wall pipe jointed by a transition weld
W_c	Length of a corrosion anomaly in pipe circumferential direction
δ_A	Apparent toughness
δ_F	Crack tip opening displacement
δ_{pipe}	Crack tip opening displacement measured on pipe side
δ_{weld}	Crack tip opening displacement measured on weld side
ε_c^{dem}	Compressive strain demand
ε_c^{crit}	Compressive strain capacity
$\varepsilon_c^{crit,2D}$	2D compressive strain capacity
$\varepsilon_{c,dent}^{crit,2D}$	2D compressive strain capacity of dented pipes
$\varepsilon_{c,dent}^{crit,ex}$	Compressive strain capacity by extrapolation of dented pipes
$\varepsilon_{c,corr}^{crit}$	Compressive strain capacity of a pipe with corrosion
ε_c^{ref}	Reference compressive strain capacity

$\varepsilon_{c,corr}^{ref}$	Reference compressive strain capacity of a pipe with corrosion
$\varepsilon_{c,gw}^{crit,2D}$	2D compressive strain capacity of regular girth welds
$\varepsilon_{c,gw}^{crit,ex}$	Compressive strain capacity by extrapolation of regular girth welds
$\varepsilon_{c,tw}^{crit,1DS}$	1DS compressive strain capacity of transition girth welds
$\varepsilon_{c,tw}^{crit,ex}$	Compressive strain capacity by extrapolation of transition girth welds
ε_e	Strain where the Lüder's extension ends
ε_t	Tensile strain
ε_{t}^{crit}	Tensile strain capacity
$\varepsilon_{t,corr}^{crit}$	Tensile strain capacity of a pipe with corrosion
$\varepsilon_{t,gw}^{crit}$	Tensile strain capacity of regular girth welds
$\varepsilon_{t,tw}^{crit}$	Tensile strain capacity of transition girth welds
$\varepsilon_{t,corr}^{ref}$	Reference tensile strain capacity of a pipe with corrosion
ε_{t}^{ref}	Reference tensile strain capacity of a regular girth weld
ε_u	Pipe uniform strain
γ_b	Safety factor applied to the burst pressure
γ_c	Safety factor applied to the compressive strain capacity
γ_{sd}	Safety factor applied to the strain demand
γ_t	Safety factor applied to the tensile strain capacity
$\gamma_{t,gw}$	Safety factor applied to the tensile strain capacity of girth weld
$\gamma_{t,tw}$	Safety factor applied to the tensile strain capacity of transition girth weld
σ_f^{thin}	Flow stress of the thin-wall pipe jointed by a transition weld
σ_{SMYS}	Specified minimum yield strength
σ_{SMYS}^{thick}	Specified minimum yield strength of the thick-wall pipe jointed by a transition weld
σ_{SMYS}^{thin}	Specified minimum yield strength of the thin-wall pipe jointed by a transition weld
σ_u	Ultimate tensile strength or tensile strength
σ_y	Yield strength
σ_{u}^{thick}	Ultimate tensile strength of the thick-wall pipe jointed by a transition weld

σ_u^{thin}	Ultimate tensile strength of the thin-wall pipe jointed by a transition weld
σ_u^w	Weld metal ultimate tensile strength
σ_y^{thick}	Yield strength of the thick-wall pipe jointed by a transition weld
σ_y^{thin}	Yield strength of the thin-wall pipe jointed by a transition weld
θ	Taper angle of transition girth weld
θ_1, θ_2	Pipe cross section rotation angles
η or R_a	Normalized depth of crack-like planar anomalies, i.e., a/t
β or R_c	Normalized length of crack-like planar anomalies, i.e., $2c/t$
ψ or R_h	Normalized weld high-low misalignment, i.e., h/t
ϕ or R_M	Weld metal strength mismatch ratio, i.e., σ_u^w / σ_u
ξ or R_{YT}	Pipe yield to tensile strength ratio, or Y/T ratio, i.e., σ_y / σ_u

7 References

1 Liu, M., Zhou, H., Wang, B., Wang, Y.-Y., Bergman, J., Ayton, B., Stephens, M., Weeks, T., and Gianetto, J., 2017, "Strain-Based Design and Assessment in Critical Areas of Pipeline Systems with Realistic Anomalies," US DOT Contract No. DTPH56-14-H-00003, final report.

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6 Dassault Systèmes Simulia Corp., 2013, "The Riks Method" in Section 6.2.4 of the ABAQUS/Standard User's Manual (ver 6.13), Providence, RI, USA

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8 Liu, M., Wang, Y.-Y, Sen, M., and Song, P., "Integrity assessment of post-peak-moment wrinkles," Proceedings of the 11th International Pipeline Conference, Paper No. IPC2016-64654, September 26-30, 2016, Calgary, Alberta, Canada

9 Liu, M., Wang, Y.-Y., Zhang, F., and Kotian, K., 2014, "Realistic Strain Capacity Models for Pipeline Construction and Maintenance," final report to US DOT PHMSA, US DOT Contract No. DTPH56-10-T-000016, October 15, 2014. http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=361&btn=Modern+Search.

Appendix A Tensile Strain Capacity Equations for Regular Girth Welds

A.1 Tensile Strain Capacity Equations

In a prior PHMSA/PRCI research project [1], a set of equations were developed to calculate the tensile strain capacity (TSC) for regular girth welds. Separate equations were developed for gas metal arc welding (GMAW) and flux-cored arc welding (FCAW)/shielded metal arc welding (SMAW) welds. For both types of girth welds, the TSC equations adopted the same form, i.e.,

$$\varepsilon_t^{crit} = \min\left(\varepsilon_u, P\left(f_p\right)G(t)\varepsilon_{t,f_p}^{crit}\right). \tag{A-1}$$

where the functions $G(t)$ and $P\left(f_p\right)$ characterize the effect of wall thickness and internal pressure, respectively. The unit of the TSC (ε_t^{crit}) is mm/mm (in/in). The function $G(t)$ is given as

$$G(t) = \left(\frac{15.9}{t}\right)^{0.8096\left[1+1.503\left(\frac{h}{t}\right)^{1.229}\right]}, \tag{A-2}$$

where, *t* is the pipe wall thickness in the unit of mm. The function $P\left(f_p\right)$ is in the form of

$$P\left(f_p\right) = \begin{cases} P_{max} - \frac{5f_p}{3}\left(P_{max} - 1\right) & if \;\; 0 < f_p < 0.6 \\ 1 & if \;\; 0.6 \le f_p < 0.8 \end{cases}. \tag{A-3}$$

A conservative fixed value of 1.5 was initially given to P_{max} [1]. A more refined relation was developed later [2] as:

$$P_{max} = 2.25 - 2\frac{a}{t}. \tag{A-4}$$

The term $\varepsilon_{t,f_p}^{crit}$ in Eq. (A-1) is the tensile strain capacity when the pressure factor (f_p) equals 0.72. $\varepsilon_{t,f_p}^{crit}$ is in the form of

$$\varepsilon_{t,f_p}^{crit} = A\frac{f(\delta_A)}{1+f(\delta_A)}. \tag{A-5}$$

The $\varepsilon_{t,f_p}^{crit}$ obtained from Eq. (A-5) is in the unit of mm/mm (in/in). The function *f* is given as

$$f(\delta_A) = (C\delta_A)^{B(\delta_A)^D}. \tag{A-6}$$

In Eqs. (A-5) and (A-6), the symbols *A*, *B*, *C*, and *D* are fitted functions of normalized geometry and material parameters. The fitted functions of *A*, *B*, *C*, and *D* for GMAW TSC are in the following forms:

$$\begin{cases} A = a_1 e^{a_2/\beta} e^{a_3 \eta \beta e^{a_4/\beta}} \left[1 + a_5 \psi^{a_6} + a_7 \psi \left(\eta \beta \right)^{a_8} \right] \left(1 + a_9 \xi^{a_{10}} \phi^{a_{11}} + a_{12} \psi^{a_{13}} \xi^{a_{14}} \right) \\ B = \beta^{b_1} \eta^{b_2 \beta^{b_3}/\eta} \left[b_4 \phi^{b_5} \left(b_6 \phi^{b_7} \right)^{\xi} + b_8 \psi^{b_9} \right] \\ C = e^{c_1/\beta} e^{\frac{c_2 \beta}{(1+c_3\beta)\eta}} \left(1 + c_4 \psi^{c_5} + c_6 \psi e^{-\eta} + c_7 \psi e^{-\beta} \right) \left(c_8 + c_9 \phi^{c_{10}} + c_{11} \xi^{c_{12}} \phi \right) \\ D = d_1 \beta^{d_2} \eta^{\frac{d_3 \beta}{(1+d_4\beta)}} \left(1 + d_5 \psi^{d_6} \right) \left(1 + d_7 \xi^{d_8} + d_9 \phi^{d_{10}} \right) \end{cases} . \qquad \text{(A-7)}$$

The normalized geometric and material parameters in the TSC equations are given below:

$\eta = a/t$ normalized flaw depth, i.e., R_a

$\beta = 2c/t$ normalized flaw length, i.e., R_c

$\psi = h/t$ normalized girth weld high-low misalignment, i.e., R_h

$\xi = \sigma_y / \sigma_U$ base metal Y/T ratio, i.e., R_{YT}

$\phi = \sigma_U^W / \sigma_U$ weld metal strength mismatch ratio measured at ultimate tensile strength, i.e., R_M

The coefficients in Eq. (A-7) are given in Table A - 1.

Table A - 1 Fitted coefficients of TSC equation for GMAW

a1	2.084E+00	b1	-5.005E-02	c1	1.409E+00	d1	2.209E-02
a2	2.812E-01	b2	-5.139E-03	c2	2.345E-01	d2	1.156E+00
a3	-4.950E-01	b3	4.485E-01	c3	1.125E+00	d3	1.601E+00
a4	7.373E-01	b4	1.417E+00	c4	4.181E+00	d4	8.964E-01
a5	-5.005E+00	b5	2.217E+00	c5	1.201E+00	d5	1.383E+00
a6	1.186E+00	b6	1.029E+00	c6	-5.384E+00	d6	1.333E+00
a7	1.644E+00	b7	-2.598E+00	c7	2.406E+00	d7	9.313E-02
a8	7.374E-01	b8	-2.679E+00	c8	-2.154E-01	d8	-2.240E+00
a9	-9.829E-01	b9	1.694E+00	c9	-5.237E-03	d9	8.559E+00
a10	8.655E-02			c10	9.889E+00	d10	-3.719E+00
a11	-1.029E-01			c11	3.547E-01		
a12	-1.500E-01			c12	-7.513E-01		
a13	1.025E+00						
a14	5.557E+00						

The fitted functions of *A*, *B*, *C,* and *D* for FCAW/SMAW TSC are in the following forms:

$$\begin{cases} A = a_1 e^{a_2/\beta} e^{a_3 \eta \beta e^{a_4/\beta}} \left[1 + a_5 \psi^{a_6} + a_7 \psi^{a_8} \left(\eta \beta \right)^{a_9} \right] \left(1 + a_{10} \xi^{a_{11}} \phi^{a_{12}} \right) \\ B = \beta^{b_1} \eta^{b_2 \beta^{b_3}/\eta} \left[b_4 \phi^{b_5} \left(b_6 \phi^{b_7} \right)^{\xi} + b_8 \psi^{b_9} \right] \\ C = e^{c_1/\beta} e^{\frac{c_2 \beta}{(1+c_3\beta)\eta}} \left(1 + c_4 \psi^{c_5} + c_6 \psi e^{-\eta} + c_7 \psi e^{-\beta} \right) \left(c_8 + c_9 \phi^{c_{10}} + c_{11} \xi^{c_{12}} \phi \right) \\ D = d_1 \beta^{d_2} \eta^{d_3} \left(1 + d_4 \psi^{d_5} + d_6 \eta \beta \psi \right) \left(1 + d_7 \xi^{d_8} + d_9 \phi^{d_{10}} \right) \end{cases} . \qquad \text{(A-8)}$$

The coefficients in Eq. (A-8) are given in Table A - 2.

Table A - 2 Fitted coefficients of TSC equation for FCAW

a1	9.281E-01	b1	-5.578E-02	c1	1.609E+00	d1	6.822E-03
a2	9.573E-02	b2	1.112E-02	c2	1.138E-01	d2	1.014E+00
a3	-5.053E-01	b3	-1.735E-01	c3	6.729E-01	d3	1.746E+00
a4	3.718E-01	b4	1.675E+00	c4	2.357E+00	d4	2.378E+00
a5	-2.023E+00	b5	2.603E-01	c5	1.057E+00	d5	9.434E-01
a6	7.585E-01	b6	1.106E+00	c6	-4.444E+00	d6	-1.243E+00
a7	6.299E-01	b7	-1.073E+00	c7	1.727E-02	d7	3.579E+01
a8	5.168E-01	b8	-1.519E+00	c8	-1.354E-02	d8	7.500E+00
a9	7.168E-01	b9	1.965E+00	c9	-1.224E-02	d9	6.294E+01
a10	-9.815E-01			c10	8.128E+00	d10	-6.930E+00
a11	2.909E-01			c11	2.007E-01		
a12	-3.141E-01			c12	-1.594E+00		

The applicable ranges of the input parameters in the TSC Equations are listed below:

η 0.05 – 0.5,

β 1.0 – 20.0,

ψ 0.0 – 0.2,

ξ 0.75 – 0.94,

ϕ 1.0 – 1.3,

f_p 0.0 – 0.8,

δ_A 0.2 mm – 2.5 mm (0.0079 in – 0.10 in), and

t 12.7 mm – 25.4 mm (0.5 in – 1.0 in).

The pipe OD (*D*) and yield strength (σ_y) are not directly used as input parameters. But, the equations are recommended for the following ranges:

D 304 mm – 1,219 mm (12 in – 48 in) and

σ_y 386 MPa - 690 MPa (56 ksi – 100 ksi).

A.2 References

1 Wang, Y.-Y., Liu, M., and Song, Y., 2011, "Second Generation Models for Strain-Based Design," final report to US DOT PHMSA, US DOT Contract No. DTPH56-06-T000014, http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=201

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Appendix B Compressive Strain Capacity Equations for Plain Pipes

B.1 Compressive Strain Capacity Equations

In a prior work sponsored by PHMSA [1], a set of equations were developed to calculate the compressive strain capacity (CSC) of plain pipes. The compressive strain capacity equations are given in the following:

$$\varepsilon_c^{crit,2D} = \min(\varepsilon_u, F_{LD} * \varepsilon_r), \tag{B-1}$$

$$F_{LD} = \begin{cases} 1 - 0.50 * (1 - 0.75\varepsilon_r{}^{-0.23})\left[1 + \tanh\left(8.0\frac{\varepsilon_e}{\varepsilon_r} - 8.2\right)\right] & \text{with Lüders extension} \\ 1 & \text{no Lüders extension} \end{cases}, \tag{B-2}$$

$$\varepsilon_r = F_{DP} * F_{YT} * F_{GI} * F_{NF}, \tag{B-3}$$

$$F_{DP} = \begin{cases} 980 * \left[0.5\left(\frac{D}{t}\right)^{-1.6} + 1.9 * 10^{-4}\right] & if\ f_p < f_{pc} \\ 980 * \left(1.06 f_p + 0.5\right)\left(\frac{D}{t}\right)^{-1.6} & if\ f_p \geq f_{pc} \end{cases}, \tag{B-4}$$

$$f_{pc} = 1.8 * 10^{-4} * \left(\frac{D}{t}\right)^{-1.6}, \tag{B-5}$$

$$F_{YT} = 2.7 - 2.0R_{YT}, \tag{B-6}$$

$$F_{GI} = 1.84 - 1.6\left(\frac{h_g}{t}\right)^{0.2}, \tag{B-7}$$

$$F_{NF} = 1.2f_n^2 + 1. \tag{B-8}$$

In the above equations, the units of $\varepsilon_c^{crit,2D}$, ε_u, ε_e, and ε_r are all %. The applicable range of the above CSC equations is determined by the range of the parameters used in the finite element analyses. The applicable range is given in the following:

(1) $20 \leq D/t \leq 104$;

(2) $0 \leq f_p \leq 0.80$;

(3) $0.70 \leq R_{YT} \leq 0.96$;

(4) $0.01 \leq h_g/t \leq 0.30$;

(5) $\varepsilon_e(\%) \leq 2.0$; and

(6) $0 \leq f_n \leq 0.40$.

B.2 References

1 Liu, M., Wang, Y.-Y., Zhang, F., and Kotian, K., 2014, "Realistic Strain Capacity Models for Pipeline Construction and Maintenance," final report to US DOT PHMSA, US DOT Contract No. DTPH56-10-T-000016, October 15, 2014. http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=361&btn=Modern+Search.

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